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PHYSICAL REVIEW.

THE CAPACITY OF MICA CONDENSERS.

By Anthony Zeleny.

THE differences in the value of the capacity of the same condenser observed in determinations made at different times (with different galvanometers) have given the impression that mica condensers are not available for measurements of high precision. The manufacturers of the best condensers guarantee an accuracy of only one fourth of one per cent. and even this is not usually trusted by the purchaser. The reason for these differences is that with the method of measurement commonly employed[1] the capacity value is dependent upon the period of the galvanometer. The condenser is charged or discharged through the galvanometer and remains in circuit with it during the whole period of the first throw. The gradual liberation of the absorbed charge produces a current which flows through the coil of the galvanometer the whole period of the throw. The longer this period the greater is the amount of the absorbed charge that affects the throw, and the greater is the value obtained for the capacity of the condenser.

This difficulty can be avoided readily and the results made independent of the period of the galvanometer by opening the circuit

[1] Jenkin, Report of British Association, 1863, p. 144; 1867, p. 483. Maxwell, Electricity and Magnetism, 1881, II., p. 383. Stewart and Gee, Practical Physics, 1891, II., p. 407. Kohlrausch, Physical Measurements, 1894, p. 382. Stratton and Milliken, Exps. in Gen. Physics, 1898, p. 83. Henderson, Practical Electricity and Magnetism, 1898, p. 212. Carhart and Patterson, Electrical Measurements, 1900, p. 227. Schluster and Lees, Exercises in Practical Physics, 1901, p. 357. Zeleny and Erikson, Manual of Physical Measurements, 1902, p. 107. Glazebrook, Electricity and Magnetism, 1903, p. 283. Miller, Laboratory Physics, 1903, p. 356.

after the whole measurable part of the free charge has passed and before a measurable amount of the absorbed electricity has been liberated. With this modification the capacities of good condensers can easily be determined to within 0.05 per cent. and an accuracy 0.01 per cent. is attainable. The intermittent current method[1] and the "instantaneous" charge or discharge method[2] have been described and used for measuring the capacity in terms of the free charge, and under proper conditions fulfil the above requirements. These methods, however, have not been employed generally because of the greater simplicity of the ordinary method and because no definite objection appears to have been raised to it, the dependence of the value of the capacity upon the period of the galvanometer not having been fully appreciated. The "capacity" although distinguished from "instantaneous capacity" appears to have been considered a definite quantity independent of the period of the galvanometer employed.

It is the object of this paper to point out the variations in the value of a capacity as determined by the ordinary method, to show the reasons for these variations and to describe a suitable and convenient apparatus for avoiding them and enabling the mica condenser to be used as a standard of precision.

THE DISCHARGE OF A MICA CONDENSER.

The curve of Fig. 1 shows how the quantity of electricity discharged by a good condenser varies with the time of discharge. It is seen that in the interval AB, which is usually less than .01 second, the whole measurable part of the free charge passes through the galvanometer. The absorbed charge begins to be liberated at the beginning of the discharge and continues to flow for a period greater than that of the galvanometer. In a good mica condenser,

[1] Maxwell, loc. cit., p. 384. Thomson, Phil. Trans., 1883. Glazebrook, Phil. Mag., 1884, Vol. 18, p. 98. Electrician, 25, 1890. Rosa, Phil. Mag., 1889, Vol. 28, p. 315. Thomson and Searle, Phil. Trans., 1890. Dittenberger and Gruneisen, Zs. f. Instrk., Apr., 1901, p. 112. Fleming and Clinton, Phil. Mag., 1903, Vol. 5, p. 493. Rosa and Grover, 1905, Bulletin No. 2, Bureau of Standards.

[2] Gray, Measurements in Electricity and Magnetism, 1888, I., p. 443. Glazebrook and Shaw, Practical Physics, 1893, p. 595. Tory and Pitcher, Manual of Laboratory Physics, 1901, p. 272.

the part of the absorbed charge which is liberated in a few hundredths of a second, AC, is too small to be measurable, but in 2.5 or 5 seconds, the usual periods of the first throw of a galvanometer needle or coil, this quantity becomes considerable. If the galvanometer circuit remains closed during the whole of this time, the total quantity of electricity, DD' or EE', affecting the throw varies in galvanometers of different periods. The value of the capacity determined in this manner is, therefore, a function of the period of the galvanometer as well as of the condenser itself. It is a variable quantity not adapted for use as an accurate standard. If, however, the galvanometer circuit is opened during the interval BC the quantity of electricity discharged is definite in amount and independent of the period of the galvanometer.

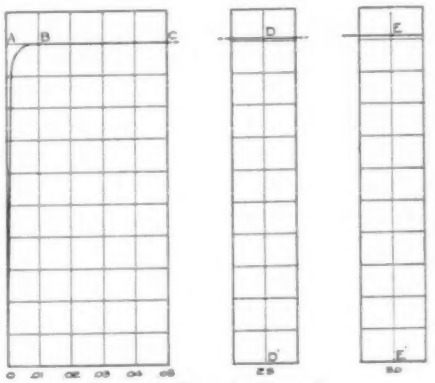

Fig. 1. Time in Seconds. Quantity Discharged.

The Discharge Key.

The special discharge key [1] adopted by the writer for determining the capacity in terms of the free charge is shown in diagram in

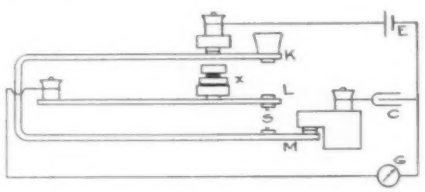

Fig. 2.

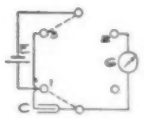

Fig. 3.

Fig. 2. In the position shown, the condenser C is being charged

[1] A well constructed (Pohl's) mercury-and-rocker commutator may be employed to accomplish the same result. The cross-bars are removed and connections made as shown in Fig. 3. The height of the mercury in the cups is adjusted so that when the rocker is turned from the charging position, shown in the figure, the cell circuit is opened first, at cup 1. The rocker then makes a contact in cup 2 before leaving cup 3, discharging the condenser during the time the two cups are in connection. The period of discharge is varied by changing the height of the mercury in cup 3.

by means of the cell E. On depressing the key,[1] the springs K, L and M are brought into metallic connection in succession. One tap on the key (1) opens the standard cell circuit, (2) discharges the condenser through the galvanometer during the time spring K is depressing the spring L to M and (3) opens the condenser circuit when the spring L depresses the spring M. The key must be held in the last position during the whole time of the first throw.

The period during which the condenser is allowed to discharge depends on the velocity of the tap and upon the length of the space S between the springs L and M. This period is varied by maintaining an approximately uniform velocity for repeated taps while regulating the length of the space S by means of the set screw X. In the key described above this space could be made of any length up to four millimeters.

Since, for a good condenser, as shown in the curve of Fig. 1, the period BC is several times greater than the period AB, the adjustment of the key and the maintenance of a sufficiently uniform velocity of tapping give no special difficulty. The operator makes the successive taps of a nearly uniform velocity and the space S is adjusted until increasing or decreasing its length does not change the amount of the throw of the galvanometer needle or coil. This space, at the writer's velocity [2] of tapping while using a galvanometer of 127 ohms resistance and observing to .05 per cent. could be of any length from 0.5 millimeter to the full range (4 mm.) of the key. If measurements were to be made to .01 per cent. the space BC would become much shorter, necessitating a greater care in adjustment. If, in any case, it were found necessary, the key could be depressed at a more uniform rate by means of a spring, or some other device could be used to accomplish the same results with greater precision.

When the space S of the key is of the proper length, successive throws agree to within one of the estimated parts of the smallest scale division, while, when too short, the usual variations in the velocity of tapping are sufficient to affect the amount of the successive throws.

[1] The springs K, L and M are not in the same vertical plane as shown in the figure. The points of contact only are in line.

[2] Roughly estimated to be about 60 centimeters per second.

The following tabulated throws of the galvanometer illustrate the action of the key. The discharges shown in Table I. were taken from a Leeds and Northrup Standard Condenser (one microfarad) using a very rapid velocity[1] in tapping the key. The space S regulating the period of discharge and the resistance of the galvanometer circuit were varied. The galvanometer resistance = 127 ohms. R = external resistance in the galvanometer circuit.

TABLE I.

R in Ohms.	Length of Space S in Millimeters.					
	0.2	0.5	1	2	3	4
0	19.25	19.82	19.82	19.82	19.82	19.82
	9.15	19.82	19.82	19.82	19.82	19.82
	11.05	19.82	19.82	19.82	19.82	19.82
500	4.59	12.45	17.95	18.50	19.82	19.82
	3.45	10.70	18.82	19.30	19.82	19.82
	3.88	11.63	18.23	19.70	19.80	19.82

Table II. gives the throws obtained with the above apparatus using different external resistances and a less rapid velocity[2] of tapping the key. A judgment of the approximate uniformity of successive velocities was obtained by a few up and down movements of the hand before striking the key. S = 1 millimeter.

TABLE II.

R = 0	R = 500	R = 1,000	R = 2,000
19.82	19.82	19.82	19.40
19.82	19.82	19.82	19.45
19.82	19.82	19.82	19.45

With this velocity of tapping the condenser can be used with any resistance in the galvanometer circuit up to 1,000 ohms.

FREE CHARGE AND ORDINARY CAPACITIES OF CONDENSERS OF DIFFERENT ABSORBING POWERS.

Table III. gives the observations taken with three condensers of different absorbing powers for the purpose of testing the possible

[1] Roughly estimated to be about 60 centimeters per second.

[2] Roughly estimated to be about 12 centimeters per second.

limits of accuracy that can be attained in measuring the free charge capacities of such condensers.

(I.) = a Leeds and Northrup mica condenser (one microfarad).

(II.) = a mica condenser of large absorbing power made in the laboratory.

(III.) = a paper condenser (" 2.8 microfarads ").

The space S of the key was measured in terms of the number of turns made by the set screw X, Fig. 1. Each turn represents a distance of one thirty-sixth of an inch or 0.706 mm. Resistance of galvanometer = 127 ohms. Period of first throw = 2.44 seconds. Velocity of tapping key = about 60 cm. per second. Two crystal cadmium cells in series were used in charging. The readings were taken on a circular scale.

TABLE III.

Condensers.	Space S in Terms of the Number of Turns of Set Screw X.										Throws, Using the Ordinary Method.
	1/8	1/4	3/8	1/2	3/4	1	1 1/2	2	2 1/2	3 1/2	
(I.)	9.60	13.11	15.70	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.83
	.10	13.54	15.71	.71	.71	.71	.71	.71	.71	.71	.83
	.25	14.10	14.60	.71	.71	.71	.71	.71	.71	.71	.83
	9.32	13.58	15.30	15.71	15.71	15.71	15.71	15.71	15.71	15.71	15.83
(II.)	11.09	12.50	15.45	15.55	15.51	15.60	15.66	15.72	15.81	15.91	18.05
	9.33	11.20	.48	.51	.56	.62	.65	.65	.70	.91	.05
	8.20	12.19	.43	.49	.56	.55	.65	.73	.75	.85	.06
	9.54	11.96	15.45	15.52	15.54	15.59	15.65	15.70	15.75	15.89	18.05
(III.)	4.54	13.26	14.70	15.00	15.45	15.82	16.33	16.92	16.92	17.81	47.24
	11.81	.63	15.82	.60	16.02	.80	.01	.90	17.50	.72	.24
	8.68	.61	14.63	.39	15.52	.84	.10	.81	16.95	.70	.26
	8.34	13.50	15.05	15.33	15.66	15.82	16.15	16.88	17.12	17.74	47.25

The observations essential for determining the point at which the whole of the free charge has passed through the galvanometer in each of the three cases are plotted in Figs. 4 and 5.

Curve I. shows that for a good mica condenser the point at which the free electricity is all discharged is definite and the residual charge produces no measurable effect for a considerable period thereafter.

Curve II. shows that for the mica condenser of high absorbing power a measurable part of the absorbed charge has affected the

throw before the whole measurable part of the free electricity has been discharged. A close estimate of the free charge can be made from the curve. It is, however, better to consider the part of the

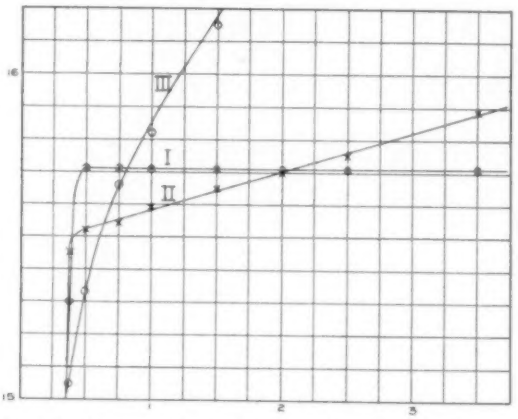

Fig. 4. Length of space S in terms of number of turns of set screw X. Throws in centimeters.

absorbed charge liberated during the interval the free electricity is discharging as a part of the free charge. With this interpretation the curve shows that the free charge capacity of this condenser can be determined to within 0.2 per cent.

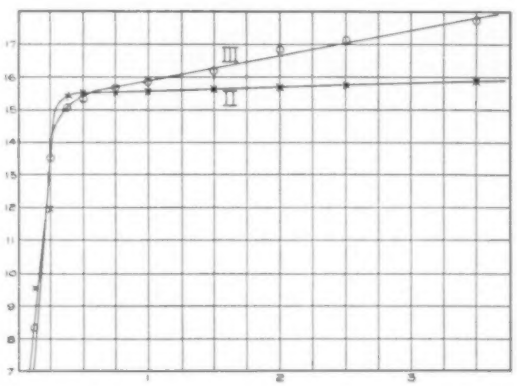

Fig. 5. Length of space S in terms of number of turns of set screw X. Throws in centimeters.

Curve III., Figs. 4 and 5, shows that in a paper condenser the free charge capacity as interpreted for condenser (II.) can be measured to within 2 per cent.

The free charge and ordinary capacities of the three condensers as determined from Table III., with the aid of the curves of Fig. 4, are given in Table IV. The free charge capacity of condenser (I.), for the purpose of comparison, is assumed to be unity.

TABLE IV.

Condenser.	Capacities.		Difference or the Capacity Value of the Absorbed Charge Effect.	Increment to Free Charge Capacity.
	Free Charge.	Ordinary.		
(I.)	(1.0000)	1.0076	0.0076	0.76 %
(II.)	0.988	1.149	0.161	16.3
(III.)	0.96	3.008	2.05	213

The effect of the absorbed charge in condenser (II.) is seen to be more than twenty times that in condenser (I.). It has been shown that the free charge capacity of condenser (II.) can be determined to within 0.2 per cent. The free charge capacity of condenser (I.), therefore can be measured to within 0.01 per cent. An inspection of curve 1, Fig. 4, confirms this conclusion.

A further test was made on condenser (I.) by taking observations to .01 per cent. The period of the first throw of the galvanometer was increased to 9″.14 by suspending lead balls on the lower end of the coil. The observations are given in Table V.

TABLE V.

Length of Space S in Turns of Set Screw X.	
3	1
94.53 cm.	
94.52	
	94.50 cm.
	94.50
	94.51
94.53	
94.52	
94.525	94.503

This shows a difference of more than .02 per cent. for a variation of the space S by two turns of the set screw. From this in connection with an inspection of the curves of Figs. 4 and 5 it is seen that the free charge capacity of this condenser can have a well defined value only to within about .005 per cent.

Capacities of Condensers Compared by Means of Galvanometers of Different Periods.

Table VI. shows the ordinary and the free charge capacities of three condensers as obtained with galvanometers[1] of different periods of vibration. The results were obtained by comparison with the free charge capacity of one of the condensers.

Table VI.

	Period of 1st Throw = 2″.25.		Period of 1st Throw = 4″.45.		Variation of Value of Ordinary Capacity.	Increment to Free Charge Capacity.	
	Free Charge.	Ordinary.	Free Charge.	Ordinary.		$t = 2''.25$.	$t = 4''.45$.
Leeds & Northrup (1 mcf.) (A).	(1.0000)[1]	1.0073	(1.0000)[1]	1.0114	0.41 %	0.73 %	1.14 %
Mica Condenser (poor) (B).	1.015	1.123	1.015	1.151	2.5	10.6	13.4
Paper Condenser ("1.2" mcf.)	0.46[2]	1.473[2]	0.46	1.559	5.8	220	239

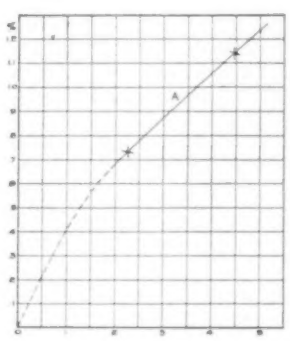

Fig. 6. Time of first throw in seconds.

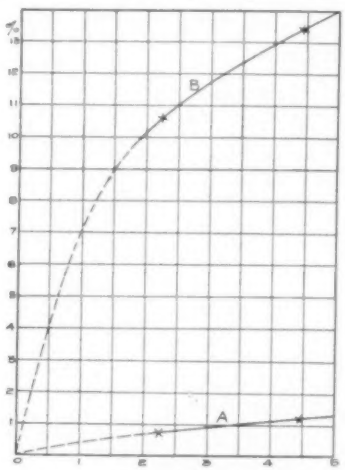

Fig. 7. Time of first throw in seconds. Increment due to liberation of absorbed charge.

The capacities in terms of the free charge are shown to be independent of the period of the galvanometer while the ordinary "capacities" vary considerably even in the best mica condenser.

[1] The galvanometers used were both of the d'Arsonval type. The one having the shorter period has an open coil and the other a cylindrical one.

[2] Value assumed for purposes of comparison.

[3] In this case the period of the first throw of the galvanometer coil was 2″.44.

The curves of Figs. 6 and 7 show, approximately, the increments to the free charge capacities of condensers A and B as the period of the first throw increases.

DAMPING OF THE GALVANOMETER DUE TO THE CONDENSER.

The damping correction,

$$\checkmark\rho = \sqrt{\frac{\theta_1}{\theta_2}},$$

was determined on open circuit and in parallel with a condenser, to test experimentally whether the condenser as used in the ordinary method had a measurable effect on the damping. An open coil d'Arsonval galvanometer was used whose coil had a resistance of 55 ohms. The capacity of the condenser was 5 microfarads.

On open circuit $\checkmark\rho = 1.0300 \pm 2$.

In parallel with capacity $\checkmark\rho = 1.0300 \pm 2$.

In the ordinary method for determining capacity, therefore, no appreciable error[1] is introduced on account of the damping due to the condenser.

RESIDUAL CHARGE VARIES AS THE E.M.F.

The amount of the first residual discharge was tested for different voltages up to 100 volts. It was found to be proportional to the electromotive force employed in charging. The capacity as determined by the ordinary method, therefore, is not influenced in value by varying the charging electromotive force.

The part of the absorbed electricity discharged during the first throw of the galvanometer coil is about one half of the first residual obtained in one minute after a discharge of the free electricity. This varies with the condenser and the period of the galvanometer.

TIME REQUIRED TO CHARGE A CONDENSER.

The difference of potential between the plates of a condenser begins to diminish immediately after the removal of the charging electromotive force on account of the gradual absorption of a part of the electric charge. The longer the time of charging the slower and smaller is the absorption after charging. A condenser must

[1] W. Einthoven, Ann. der Physik, 1905, 16, p. 20.

therefore be charged for a sufficient length of time so that during the interval between the opening of the battery circuit and the discharge no appreciable absorption takes place.

The following observations, Table VII., were taken with the Leeds and Northrup condenser. A Crystal cadmium cell having an internal resistance of about 720 ohms was used as the charging battery. The condenser was short-circuited after each observation. It was then charged for a known period and after charging allowed to stand ten seconds before the discharge.

TABLE VII.

Time of Charging in Seconds.	Throw After Standing 10″.	Per Cent. of Charge Absorbed.
1	19.68 cm.	.75
5	19.73	.50
10	19.76	.35
15	19.79	.20
30	19.81	.10
60	19.815	.07
200	19.82	.05
300	19.83	.00
600	19.83	.00

The last two observations are the same as those obtained when the discharge was made immediately after opening the battery circuit. The condenser during the five minutes of charging had absorbed almost its maximum amount so that during the interval of ten seconds the additional part of the charge absorbed was not measurable. Fig. 8 is drawn from the data of Table VII.

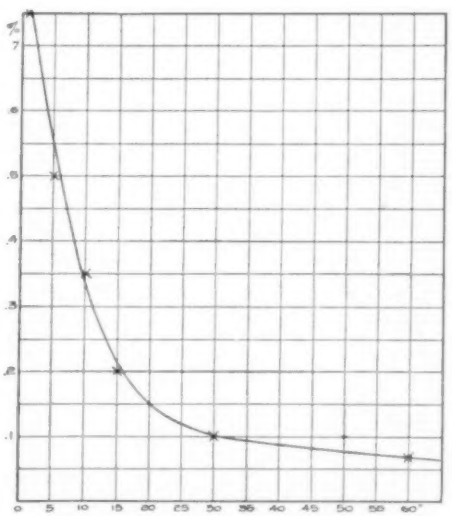

Fig. 8. Time of charging in seconds. Part of free charge absorbed.

When the observations were repeated without short-circuiting the condenser after each discharge, practically the same

throws were obtained as before. This is due to the residual charge being nearly all liberated during the interval the condenser remains discharged. The condition of the condenser in the two cases is therefore practically the same.

When the condenser is used with the special key of Fig. 1, it is discharged almost immediately after the opening of the battery circuit. After charging the condenser one second a discharge with this key gave the maximum throw of 19.83 cm. The amount of absorption during the short interval between the opening of the cell circuit and the discharge is not measurable. When using this key, therefore, it is not necessary under ordinary conditions to give any attention to the time of charging.

Absolute Measurements.

The method here described necessitates for absolute measurements the determination of the constant of the ballistic galvanometer and the observation of a scale reading. These limit the attainable accuracy to one part in 10,000 or to .01 per cent. The intermittent current method when properly used is capable of a somewhat higher accuracy in terms of a resistance standard. For ordinary laboratory determinations, however, the method described in this paper will be found simpler and more convenient.

Comparison Measurements.

The free charge capacities can be compared to .01 per cent. by the direct deflection method. It is however preferable to use a differential method when measurements are to be made with an accuracy greater than 0.1 per cent. The writer has found the two following methods satisfactory.

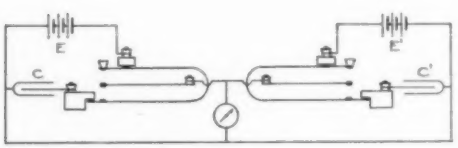

Fig. 9.

I. Each condenser is connected to a battery and a special discharge key in the usual manner except that the galvanometer used is common to both circuits and the poles of the batteries are placed in reverse order so that only the difference in the two quantities

held by the condensers affect the galvanometer throw. The essential arrangement of the apparatus is shown in Fig. 9. The two keys are depressed by a lever (not shown in the figure) so that both condensers are connected to the galvanometer at the same instant.

(A) If the two charging electromotive forces are equal

$$q = Q - Q' = (C - C')E$$

$$C' = C - \frac{q}{E}$$

The quantity q can be made as large as desired by using the proper charging electromotive force. It is measured by comparison with a discharge from the standard condenser.

(B) If the two charging electromotive forces are only approximately equal

$$q = Q - Q' = CE - C'E'.$$

Interchanging electromotive forces,

$$q' = Q_2 - Q_3 = CE' - C'E.$$

Then

$$q + q' = (C - C')(E + E')$$

and

$$C' = C - \frac{q + q'}{E + E'}.$$

(C) When the two capacities differ greatly in value the charging electromotive forces used are such as to give approximately equal quantities of electricity in the two condensers. Then

$$q = CE - C'E'$$

and

$$C' = \frac{CE - q}{E'}.$$

In case (A) comparisons can be made to the limit of agreement of the two electromotive forces. In case (B) the quantity $(q + q')/(E + E')$ can be determined to within .01 per cent. if the condensers can withstand the electromotive forces necessary to produce a throw of sufficient magnitude. If two capacities differing

in value by 1 per cent. have this difference measured to .01 per cent. a comparison is made to one part in a million or to .0001 per cent. This lower limit, however, has little meaning and ordinarily is difficult or impossible to be attained on account of the inequalities of the absorbed charges.

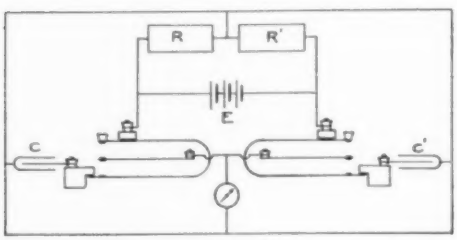

Fig. 10.

II. Another method of comparison is the well-known Thomson's method of mixtures except that the special discharge keys are substituted for the Pohl commutator ordinarily used.

The diagram of the apparatus is shown in Fig. 10. When R and R' are adjusted until no throw is obtained while depressing the keys

$$\frac{C}{C'} = \frac{R'}{R}.$$

CONCLUSION.

The capacity of a mica condenser as determined by the ordinary direct deflection method is a variable quantity and a function of the period of the galvanometer. It represents neither the unabsorbed free charge nor the total quantity of electricity held by the condenser. The capacity determined from the free charge is independent of the period of the galvanometer and dependent on the condenser only. Standards of precision must be rated, therefore, in terms of the free charge.

An interval of several hundredths of a second exists between the time of discharge of the free electricity and before the liberation of a measurable quantity of the absorbed charge. The condenser circuit must be opened during this interval. This is most conveniently accomplished by means of a special key. To avoid a loss of the free charge due to the absorption of the condenser the discharge should preferably take place immediately after charging, or the time of charging must be continued for several minutes.

The ordinary methods employed for comparing the capacities

of condensers must also be modified so as to compare the free charges only.

The free charge capacity and the temperature coefficient[1] of a condenser being known, it becomes an instrument of precision especially useful for the accurate determination of the constants of ballistic galvanometers. For this purpose each physical laboratory should contain a condenser whose free charge capacity, including the temperature coefficient, is known to .01 per cent. The accuracy of the constants of ballistic galvanometers as determined by the condenser method employing the usual discharge key cannot be assured even to within one per cent., while with the method described in this paper it should be limited only by the accuracy with which the ballistic throws can be read.

From the considerations given in this paper and since the absorbed charge is not in the true sense a measure of a part of the capacity of a condenser the following definition appears to be more appropriate than that in present use: The capacity of a condenser is the quantity of electricity it retains *unabsorbed* while its plates are at a difference of potential of one volt.

In some cases the condenser is employed in a manner where the time is too short to allow it to become fully charged or discharged or the time is of sufficient length to cause either a part or the whole of the absorbed charge to become effective. In such cases the observed capacity value should be designated by some such term as *effective capacity*, the value being definite for that particular condition of employment only.

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[1] Appleyard, Phil. Mag., 1896, Vol. 46, p. 148. Cassie, Phil. Trans., 1890, Vol. 181, A, p. 1. Terry, PHYS. REV., Sept., 1905, p. 193. Rosa and Grover, *loc. cit.*, p. 185.

PROCEEDINGS

OF THE

AMERICAN PHYSICAL SOCIETY.

MINUTES OF THE THIRTIETH MEETING.

THE Annual Meeting of the Physical Society was held in Fayerweather Hall, Columbia University, New York City, on Friday, December 29, and Saturday, December 30, 1905.

The Presidential Address of President Barus, on "Condensation Nuclei," was delivered on Saturday, December 30, at 11 A. M.

Friday afternoon, December 29, a joint session of the American Physical Society and the American Mathematical Society was held in Havemeyer Hall, at which a paper on the "Experimental Demonstration of Hydrodynamic Action at a Distance" was presented by Victor Bjerknes.

The following papers were presented:

1. The Electrical Production of Ozone. A. W. Ewell.

2. Some Properties of the Alpha Rays from Radium, II. E. Rutherford.

3. On the Magnetic and Electric Deviation of the Alpha Rays. E. Rutherford.

4. The Absorption of Alpha Rays in Gases and Vapors. E. P. Adams.

5. The Heating Effect produced by Roentgen Rays in Different Metals and their Relation to the Question of Changes in the Atom. H. A. Bumstead.

6. An Attempt to Explain the Cause of the Pressure Shift and the Broadening of Spectrum Lines. W. J. Humphreys.

7. Thermoelectric Heterogeneity in Certain Alloys. E. H. Hall.

8. The Relative Conductivities imparted to a Flame of Illuminating Gas by the Vapors of the Salts of the Alkali Metals. F. L. Tufts.

9. On the Specific Electrical Potentials of Metals in a Chemically Inert Atmosphere. C. B. Thwing.

10. The Optical Properties of Carbon. H. A. Clark.

11. Dispersion in Electric Double Refraction. H. L. Blackwell.

12. The Optical Properties of Extremely Thin Films. Wm. B. Cartmel.

13. The Thermodynamic Temperature Scale. Edgar Buckingham.

14. Differential Temperature Records in Meteorological Work. C. H. McLeod and H. T. Barnes.

15. On the Velocity of Sound in Gases at Low Temperatures and the Ratio of the Specific Heats. S. R. Cook.

16. A New Determination of the E.M.F. of the Clark and Cadmium Standard Cells by means of an Absolute Electro-dynamometer. K. E. Guthe.

17. Experiments on Resonance in Wireless Telegraph Circuits. G. W. Pierce.

18. Methods of Soil Hygrometry. Edgar Buckingham.

19. Longitudinal Vibrations Analogous to those of a Violin String. H. N. Davis.

20. On the Use of the Wehmet Interrupter with the Righi Exciter for Electric Waves. A. D. Cole. (Read by title.)

21. Notes on the Possible Separation of Electric Charges by Centrifugal Accelerations. E. F. Nichols. (Read by title.)

22. The Adjustment of the d'Arsonval Galvanometer for Ballistic Work. Frank Wenner.

23. The Purpose and the Present Condition of the Mount Weather Research Observatory. W. J. Humphreys.

24. An Electrically Controlled Thermostat operable at Room Temperatures. Lyman J. Briggs.

25. On the Use of Centrifugal Force in Soil Investigations. Lyman J. Briggs.

On Saturday morning, tellers being duly appointed, the ballots received in the annual election of officers and members of the council were counted, and the following named were declared elected: *President*, Carl Barus; *Vice-President*, Edward L. Nichols; *Secretary*, Ernest Merritt; *Treasurer*, William Hallock; *Members of the Council*, R. A. Millikan and A. Trowbridge.

ERNEST MERRITT,
Secretary.

CONDENSATION NUCLEI.[1]

BY CARL BARUS.

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INTRODUCTORY.

Steam Jet. — Before attacking the subject[2] proper, it may pay us to review the prominent methods of observing nucleation. The least pretentious of these is the transparent steam jet, which clouds up when the

[1] Presidential address before the American Physical Society, Dec. 30, 1905.

[2] References to my papers will be abbreviated as follows: B. W. B., Bulletin U. S. Weather Bureau, No. 12, 1893; S. C., Smithsonian Contributions, of the year and number specified; C. P., Carnegie Publications, No. 40, 1906.

nuclei (caet. par.) exceed a certain number per cubic centimeter. If a millimeter steam jet actuates an air current through a 2-inch tube about 3 ft. long, sky-light guided axially through the tube becomes vividly colored in the presence of increasing nucleation, long before the opaque state sets in, and again beyond it. Loci of like color[1] may be mapped in a graph in which steam pressure and air temperature are the variables; in such a case a march at any temperature from lower to higher steam pressures, is a march from lower to rapidly higher supersaturation, and at the same time a march from purple, yellow, green and blue fields through

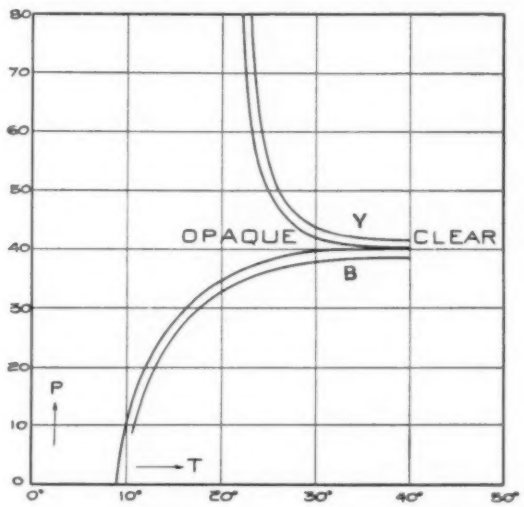

Fig. 1. Thermal topography of the steam jet, ordinates, steam pressure in lbs. per sq. inch; abscissas temperature of the inflowing air in degrees centigrade. To the right of the margin of the opaque field, the loci of blue (lower curve) and of yellow (upper curve) axial color are indicated.

opaque into brown and yellow fields. A definite degree of supersaturation is thus identified with a definite color at a given air temperature, and this constitutes the means of observation. Though the supersaturation of the steam jet may be made enormous, it does not respond usefully unless the nuclei (large or small) are present in millions per cubic cm.; for the axial colors which are evoked, require great density of nucleation to be perceptible. Ordinary atmospheric air with its tens of thousands of dust particles scarcely affects it; nor will it do so if energised by relatively weak nucleators like the X-rays or radium.[2] An order

[1] B. W. B., chaps. II. and III.

[2] These in fact usually decrease the number of efficient nuclei, as the ions are larger than the colloidal nuclei.

of nuclei of a magnitude in question may therefore be disregarded and the air entering the steam tube treated as dust-free. This is often an advantage where excessively dense distribution of excessively fine nuclei (like those which make up a structural part of dust-free air) are to be examined. The instantaneous indication and the continuity of action of the steam jet are often further advantages. Disturbances which may be produced by sudden exhaustion and by low pressure and temperature are also absent.

Fog Chamber. — The condensation chamber in which nucleated air saturated with vapor is suddenly cooled by exhaustion, is in a measure supplementary to the steam jet, if the coronas are to be examined in all their essential features, inasmuch as it subserves the purposes of measurement best when the nucleations are fractions of a million. To be effective in the capture of very fine nuclei, its dimensions will usually have to be decreased for mechanical reasons, and the coronas may then appear only in fragments of their discs. The fog chamber of large bulk capable of entrapping widely different gradations of nuclei is thus like the steam jet, apt to be an empiric instrument; *i. e.*, the amount of cooling, the supersaturation, the water precipitated per cubic cm., cannot be computed without misgiving. In the perfected and very small form designed by C. T. R. Wilson, the data seem to warrant such a procedure; though I think there is still room to be in doubt as to what happens during the rise of temperature (heat being radiated inward from without) after complete condensation. Large coronas are characteristically fleeting and variable.

Fog Limit. — A variety of fog-chamber methods are available for specifying the nucleation as to size or number, each of which may be used empirically alone. The most accurate of these, but also the most cumbersome, is Wilson's[1] method of fog limits. There are two such points, the first being given by the supersaturation at which rain-like condensation appears (somewhat over four-fold); the second by the supersaturation required to produce cloud-like condensation (about eight-fold). Both are determined with astonishing accuracy and are of very nearly the same value (volume expansions 1.25 to 1.26 and 1.375, respectively) in the non-coercible gases. The upper limits of the orders of sizes of nuclei, corresponding to the gas in any special condition, energized or not, are measured in terms of the same datum. The actual sizes of the fog particles and the number of nuclei of the kind specified are not at once determinable by this method; but an estimate may be hazarded as to the size of the nuclei. The distribution of sizes below the maximum and their numbers are obviously beyond the scope of the method, and this has been the chief aim of the work to be summarized below.

[1] Wilson's fundamental experiments may be found in Phil. Trans. London, Vol. 189, 1897, pp. 265–307; Vol. 192, 1899, pp. 403–453; Vol. 193, 1899, pp. 289–308.

Coronas. — The most expeditious of the relative methods for estimating numbers and sizes of fog particles is based on the measurement o coronal apertures.[1] As a method, this is naturally much less accurate than the preceding ; but since the apertures vary between wide limits they are admirably suited for exploration, if the same supersaturation (*i. e.*, the same volume expansion) is used throughout. Two methods are again available, the first depending upon the direct measurement of the diameters of coronas ; the second upon the reduction of the limiting size of coronas, or more specifically on the depression of the terminal asymptote corresponding in any given fog chamber to the normal case of dust-free air. The coronal method should at once suffice for the measurement of the diameters of fog particles and the nucleation would then follow from the given precipitation per cubic centimeter. Unfortunately the treatment of the diffractions even of a single small particle is a severe problem, needing (as Lommel has shown) an extensive application of Bessel's functions. It is not remarkable, therefore, that the case of indefinite assembly of particles has not been adequately stated.

Standards.[1] — In the absence of trustworthy theoretical data, the coronas must be standardized either by results obtainable or from the subsidence of fog particles whose coronas are known, or by using particles of an otherwise known diameter, or by an approximate use of diffractions under simplified conditions. With these admissions the color phenomena may be classified with a view to the determination of sizes and numbers of particles, by the aid of successive identical exhaustions into what may be called geometric sequences of coronas.

Colors.[2] — The bewildering gorgeous array of colors observed in the successive coronas for particles all of the same size, but decreasing slowly in diameter from experiment to experiment, falls naturally into three groups. In the first we may put the diffraction annuli proper, which gradually enlarge with changes of color without limit ; in the second come the colors of the disc, originally white, but more and more vividly colored as the coronas are larger, and following each other in spectrum order, approximately, when the successive experiments are made with particles of decreasing smallness. On using the electric light as a source, a remnant of white disc seems, however, to remain immediately around the source. Finally the axial colors, which are identical with the colors of the steam jet, make up a third group, and they are nearly complementary in tone with the corresponding disc colors. The whole subject still needs systematic investigation. The axial colors essentially overlie or color the source of light even if this is 6 inches square, and it thus appears as if the disc colors emit the light which is axially absorbed. These phenomena are even more vivid in hydrocarbon vapors.

[1] S. C., No. 1373, chap. III. ; S. C., No. 1651, chaps. III., VI., VIII.

[2] S. C., No. 1651, chap. VI.

Apertures.[2] — The aperture of coronas is best measured to the outside of the first ring, as the contrast here between red and blue, or red and green, if ordinary light is used, is sharpest. The white and colored discs soon become vague in outline. The light should be remote from and the goniometer near the intervening fog chamber. Apertures will be found to increase as a whole, but at the same time to vary periodically with the decreasing size of fog particles. In other words, periodic variation is superimposed on regular variation, as each successive cycle of colors is run through. The cycles are definitely separable for the larger coronas; for the smaller coronas they are so crowded together as to nearly escape detection. This is rather fortunate from the practical point of view, for it admits of the measurement of nucleations below a few thousand from the apertures alone without taking into account the changes of cycle.

Subsidence. — Stokes' subsidence equation for small spherical particles is an invaluable aid for the measurement of diameters of fog particles. The use of the equation in connection with the subsidence of clays, which I made extensively[1] in 1886, did not furnish as much evidence as was anticipated; but in the case of fog particles the conditions are apparently ideal. The outstanding difficulty seems to be that the observed motions for the case of small coronas are accelerated, whereas large coronas are fleeting and change character utterly during the period of subsidence, while in general the fog line is not sharp.

Photography.[2] — Much may be learned about the distribution and size of nuclei by photographing the fog particles formed upon them, a method which has but been begun. It has been shown, however, that fog particles in a capacious fog chamber may be caught on a film of viscous oil, either for measurement under the microscope or for micro-photography. As the requirement is that of photographing drops of the order of one ten-thousandth cm. and less, it is clear that the isothermal and other conditions must be regulated to a nicety.

The endeavor to use these photographs to determine the nucleation directly, as well as to measure the diameter of fog particles runs counter to serious difficulties; but nevertheless particles of extreme fineness corresponding to the large green-blue-purple coronas and of the diameter specified have been successfully taken. It is noteworthy that whereas the photographic values for the diameters are too large and the corresponding photographic nucleations are too small, the datum computed from both for the quantity of water precipitated per cubic cm. in any given exhaustion is roughly correct.

Thus far, moreover, fog particles condensed on persistent nuclei only,

[1] Am. Journ. Sci., Vol. 37, 1889, p. 122; Bull. U. S. G. S., No. 36, 1886.

[2] S. C., No. 1651, chap. VII.

have been photographed. Particularly in the case of the X-rays they show pronounced gradations of size compatible with the blurred coronas, and indicating the occurrence of correspondingly graded nuclei. The more important problem of photographing fog particles condensed on ions has not yet been attacked; but it presents no special difficulty beyond the cases already mastered, and it is clear that a number of important questions would be thus answerable.

Nuclei in General.

1. *Nucleation.* — The novelty and importance of the results which have accrued from investigation of the condensation of vapor precipitated by ions, has withdrawn the attention of most physicists from the functions and occurrence of the nucleus; and yet nucleation is probably the question of larger scope as it embraces not merely the physical structure of gases, but possibly even chemical affinity. It will appear, for instance, that in case of such a simple system as moist air, there is presented an apparent continuity of phases merging into, if not transcending the molecules themselves.

2. *Persistent Nuclei.* — Classified in the order of smallness, we may recognize three types of nuclei. The members of the first class are usually foreign to the gas in which they are suspended; but this is by no means necessarily so, as they may be produced in dust-free air by intense and prolonged X-radiation, or again by ultra-violet light. It is the characteristic of these nuclei that they require scarcely any supersaturation to induce condensation, that they are persistent, and that they can be separated from the gas in which they are otherwise universally present, by filtration. The term "dust" has been given to them with some justification; but this term is misleading; insofar as they enter saliently into the group of phenomena to be considered in the present address, they represent something indefinitely finer; and (with a single exceptional group) they almost always arise in an intensely ionized field. I should prefer to call them Coulier's or Aitken's nuclei, or perhaps better still, persistent nuclei.

3. *Fleeting Nuclei Ions.* — The class of nuclei next in the order of smallness are the ions. Nuclei of otherwise the same properties may however be produced, unassociated with an electrical charge, and it is suggestive that their maximum size need not be very different from that of the ions. This (as Wilson has shown) is definitely limited, requiring a supersaturation exceeding four times the normal value to induce condensation. The ions are thus, virtually at least, much below the order of size of the persistent nuclei. Moreover they are characteristically fleeting. Below the maximum dimensions they apparently show all gradations of size, and the term fleeting nuclei is not inapt. What their minimum size may be with

increasing electrification is left open, as they merge into the nuclei of dust-free air from which they are then very difficult to distinguish. As their name implies the ions invariably carry electrical charge; but whether both entities, the fleeting nuclei and their charges, vanish at the same rate is yet to be determined. The rates are nearly the same; but on the other hand fleeting nuclei occur without charges and evanescence is very generally a function of size.

4. *Colloidal Nuclei.* — The class of nuclei next in succession is a fixed structural constituent of the gas itself. The nuclei do not carry appreciable electric charge. Their maximum size is also definitely limited as they require at least an eight-fold supersaturation to induce coronal condensation. If withdrawn from the gas they are at once restored, and are therefore essential to its chemical equilibrium. Below the maximum size they are graded, as the steam jet shows conclusively. Their minimum size is quite indefinite. It may terminate in the molecule or it may go even beyond. I prefer to regard the molecule as merely a dimension of nucleus repeated with maximum frequency because adapted to the given environment; and there is no reason why there should not be particles of ultra-molecular size permanently present within the gas to the same degree in which there are uniform gradations of particles of larger size up to the maximum. In fact with the discovery of the existence of free electrons under other conditions, such inferences are no longer disturbing.

Nuclei of the present type may be fitly called colloidal, as there is need of a distinctive name and the term colloidal nucleus is sufficiently vague.

5. *Electrons.* — Finally beyond these nuclei and in the direction of increasing smallness, the quest will be terminated by the electron itself. It would however be idle to attempt to specify what permanently resides in a gas at normal pressures beyond the colloidal nucleus, from the bearings of the present body of facts.

6. *Periods.* — If we cast an eye cursorily over the whole range of nuclei thus briefly sketched, we may note that in a march of decreasing size the alternate groups are usually ionized. The periodic occurrence of electrical quality as the dimensions of the nuclei grow continually smaller is probably fanciful; for the fleeting nuclei at least may be produced without ionization.

I shall now invite your attention to a brief review of the properties and occurrences of the successive ranges of nucleation, beginning with Aitken's or the

Persistent Nuclei.

7. *Sources. Absorption.* — The nucleus at the outset, is merely a dust particle, small enough to float in the air, but larger than the order of molecular dimensions. Such a particle precipitates condensation in an

atmosphere sufficiently supersaturated with water or other vapor in its immediate vicinity, for the reasons long ago pointed out by Lord Kelvin (1880). Experimental support of this explanation had already been given by the work of Coulier (1875), and later in the investigation of Kiessling (1884 et seq.), of the younger Von Helmholtz (1886 to 1887), and in the atmospheric investigations of John Aitken (1880 to 1888).

Isolated nuclei however, would interest us but little; it is when they occur in thousands and in millions that they give rise to condensational phenomena of importance in the economy of nature. To produce these legions of nuclei is not impossible by mechanical means, just as we can for instance triturate a solid to a degree of impalpable fineness; but the more powerful agencies are usually chemical or at least refined physical processes. Similarly though a class of very interesting nuclei may be obtained by vigorously shaking solutions, or better by shattering the liquids in mutually impinging jets or jets impinging on a solid obstacle, nuclei are more abundantly produced by the evaporation (otherwise inappreciable) of certain concentrated hygroscopic liquids like sulphuric acid; or again by ignition, by combustion, etc. Such ignition should not be accompanied by any kinds of smoke, as the gross particles in this case are either a means of absorbing nuclei, or they capture too much of the available moisture. A clear Bunsen flame, a metal or any other solid (like glass) at a temperature approaching red heat or beyond, is a powerful nucleator. At ordinary temperatures phosphorus is subject to a peculiar kind of slow combustion, whereby nuclei are produced at 13° C. or a little below, and then produced from the smokeless body in maximum abundance. Many gaseous sulphides, the fumes of poly-sulphides, or of sulphur chloride on mixture with air, are good nucleators. Even dust-free coal gas and dust-free air, on commingling, set free nuclei probably belonging to this category.

In addition to mechanical, thermal and chemical processes, high electrical potential is a fruitful means of producing nuclei. A metal highly charged with electricity or even a glass insulator or the nodal points in the pathway of a stationary electric wave are a source of nuclei. There need be no spark, but an electric glow is in such cases probably always in evidence.

Finally certain kinds of radiation like strong ultra-violet light, or the X-rays acting with great intensity at short ranges and for a period of minutes, give rise to persistent nuclei in the dust-free air through which the radiation passes.

This means of producing them is the most interesting as they come in contact with no foreign bodies other than the walls of the vessel which holds the gas, and persistent nuclei may be produced by the X-rays within walls of water. At high exhaustions this growth of such persistent nuclei

may be traced by the gradual depression of the terminal corona of dust-free air, as the exposure is more and more prolonged.

Air subjected to any of these sources is more or less filled with the freight of nuclei, and we have for brevity introduced the term *nucleation*, to denote the number of nuclei per cubic cm., regardless of kind or origin or other properties possessed, and considered solely with respect to their tendencies to promote condensation in a supersaturated vapor. If the nuclei left without interference outlive the period of many minutes or hours, we have called them persistent. On the other hand we have applied the term *ionization* (by contrast) to the number of electrons per cubic cm., regardless of the nuclei with which they may be associated.

An interesting property of the persistent nucleus is its absorption[1] at the walls of a vessel, or more obviously in tubes. If these are not too wide, the absorption takes place at the same rate irrespective of the diameter and substance of the tube. Since the decay of persistent nuclei is relatively negligible, the phenomena in case of phosphorus nuclei proceeds as if each nucleus of a nearly saturated region traveled in the entire absence of an electric field, with a velocity of about 3 millimeters per second; or if about $\pi/16$ of the entire number travel in a given cardinal direction, as though each nucleus had a velocity approaching 1.5 centimeters per second.

8. *Atmospheric Nucleation.* — As the sources of nuclei just referred to are such as are continually in presence in civilized communities, it is clear that the atmosphere must be loaded with nuclei, particularly so in winter, with those arising from the originally ionized products of combustion. But it would be rash to assume that the only sources of such nuclei are local or artificial, seeing that the artificially produced ionization, from its more rapid decay in comparison with the nuclei here in question, contributes nothing to atmospheric ionization. Apart from this, highly nucleated air, no matter whence the nuclei may arise, deserves attention as a medium not only of special properties and universal occurrence, but as affording opportunities for research. As the older and classic observations on kindred subjects were incidental or sporadic, it seemed that a continuous record of atmospheric nucleation taken systematically throughout a number of years would fully repay the labor of date-gathering, even on the theoretical side. From the practical side, all researches which depend on the radiation received from the sun, in meteorology or astro-physics, are in a measure furthered by a knowledge of the time and space distribution of the persistent nuclei in the atmosphere. Accordingly such a survey was begun at Providence over three years ago,[2] and is still in

[1] S. C., No. 1309, chap. III.; No. 1651, chaps. I. and II.

[2] S. C., No. 1651, chap. IX.

progress, and during the last winter the work was supplemented by parallel observations made at Block Island.[1] Since July, moreover, contemporaneous series of data for the nucleation and ionization of the atmosphere have been recorded. Four observations were usually made daily, and in these much of detailed interest, which must be passed over here, is apparent.

In the discussion of this large body of observations, it is expedient to compute the daily means and from these to derive the average nucleation for the successive months during the period of observation. In graphs

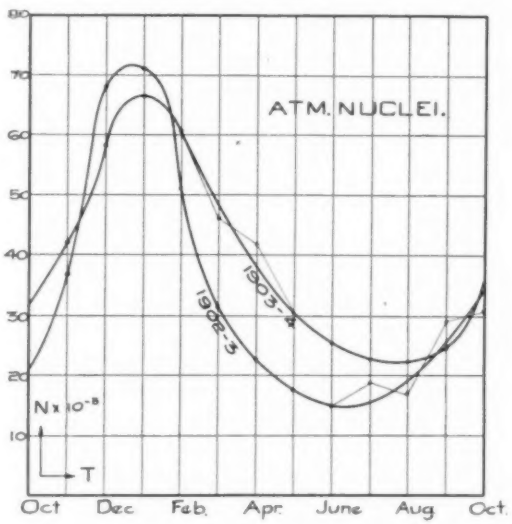

Fig. 2. Nucleation at Providence, R. I., in thousands of nuclei per cubic centimeter. The ordinates are the averages found for the successive months stated, during the years 1902–3 and 1903–4.

of this character the similarity as well as the divergence of nucleations is cogently presented. As a rule the run of incremented nucleation follows the run of decremented temperature, in a general way, throughout the year, but with more or less detail during the winter months. Again, while the nucleation curves are specifically distinct for each of the years of observation (into the details of which I cannot enter), they all have the common tendency to show sharp maxima of a value approaching one hundred thousand per cubic centimeter, at about the time of the winter sosltice, and flat minima somewhat exceeding ten thousand per cubic centimeter, near the summer solstice. It is clear from the enormous differences involved, that astronomical causes cannot be directly opera-

[1] C. P., No. 40, chaps. IV., V.

tive, apart from the fact that the origin of the nucleation is in large measure local; but even if we agree that nucleation is powerfully depressed by rains and damp snows and possibly also (from the length of the summer day) by light pressure, the time of the winter maximum does not coincide with the period of maximum cold and of maximum combustion. A more complicated explanation is thus needed, or in any event something non-local is superimposed on what may be regarded the fairly uniform local nucleation of the winter months.

To throw light on this question, *i. e.*, to ascertain whether there may be room for a cosmical effect obscured at Providence by the dominant

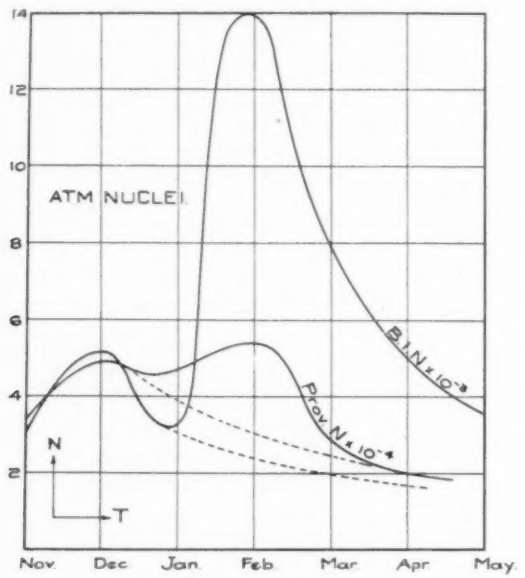

Fig. 3. Average monthly nucleations at Providence and at Block Island during the successive months stated in 1904–5. The former are given in ten thousands of nuclei per cubic centimeter, the latter in thousands of nuclei per cubic centimeter.

local distributions, observations must be made at a station where the atmosphere is less contaminated by the products of the activity of an industrial community. Block Island seemed an ideal station for the purpose, inasmuch as it would be subject to about the same meteorological changes of wind and weather as Providence, while the former is (in winter at least) nearly free from local effect. Moreover, Block Island is surrounded by a body of water, the least radius of which is nearly twenty kilometers from the center of the island, while over one half of it fronts the ocean. In any event different bodies of air would come under observation. Accordingly, measurements were taken last winter simultane-

ously at the two stations (at Block Island by Mr. R. Pierce) by the same coronal methods.

When the curves of monthly nucleation for each place had been calculated, both suggested the results of the two preceding years, the tendency being to reach sharp maxima of nucleation in December with a rapid fall thereafter to the flat summer minimum. In both cases, however, there was a new effect in February, 1905, which, being superimposed on the high local nucleations at Providence, appears as a mere departure from the normal curves, but which juts out into striking prominence in the observations at Block Island, where the local effect is relatively negligible. Apart from quantity the fluctuations of both curves are of the same kind. Remembering that different bodies of atmospheric air arrive at the two stations, one may conclude conservatively that the coincident variations represent the diluted local effects arising on land elsewhere, but averaged by the sweep of the winds for an enormous extent of territory. It is true, too, that the minimum monthly temperature was felt in February; but neither this nor the rain distributions are adequately pronounced in their variations, to be comparable with the cotemporaneous nucleations at Block Island. It is therefore quite justifiable to depart from strict prudence in believing that at least the February maximum may represent an actual invasion of the atmosphere, on the part of some external nuclei-producing agency; and that both the nucleations *and the temperature* may have been effects of the same cause. Time alone can discriminate between these surmises.

9. *Solutional Nuclei.*[1] — If pure water is shattered into fine spray the particles must soon evaporate even in a saturated atmosphere, under the conditions of the increasing temperature which follows the sudden cooling in the fog chamber; particularly so, as with decreasing size of particle, the vapor pressure at the surface continually rises. If the liquid is a solution, however dilute, a point will be reached at which the increment of vapor pressure due to increasing curvature is equivalent to the decrement of vapor pressure due to diminishing bulk and increasing concentration. Evaporation thereafter ceases, and the particle which is now remarkably persistent in the saturated environment, may be called a water nucleus. The very frequent occurrence of rain in connection with large coronas and relatively small fog particles is referable to water nuclei.

Here probably belong the nuclei obtained from certain hygroscopic liquids like the concentrated mineral acids, all of which are remarkable nucleators and make up a class by themselves, inasmuch as the nuclei are quite without ionization. A thousand or a million or more molecules per cubic cm., may escape unobserved from such a body into the surrounding air by ordinary evaporation, in spite of the low vapor pressure.

[1] S. C., No. 1373, chap. V.

The nuclei would be formed in a saturated atmosphere by condensation of water vapor. Sulphur and sulphide nuclei (the former most abundantly produced by the sulphur flame though emitted at a temperature almost as low as the melting point), sulphur-chloride nuclei, etc., are probably of like nature, being oxidized into sulphuric acid. They are also non-ionized.

It is not necessary, however, to make use of hypotheses; for water nuclei may be abundantly produced by merely shaking solutions,[1] or in vast numbers up to several hundred thousand per cubic cm. by high pressure jets and sprays. Wherever in experiments of the present kind, there is wheezing or bursting of small bubbles, annoying discrepancies due to water nuclei are liable to occur. The number of nuclei obtained by identically agitating solutions varies naturally both with the solvent, the solute, and the amount in solution. Identically shaking one per cent. solutions and computing the nucleation resulting from the coronas observed in each case, one may classify the results somewhat as follows: pure water 100, aqueous solutions of organic bodies 600, aqueous solutions of mineral salts 1,300, benzol solution of naphthalene or paraphine 3,000 or 5,000. It is difficult to conjecture an explanation for this demarcation of groups.

Moreover the persistence of the solutional nucleus is in direct relation to the number of nuclei produced. They are more fleeting as the solutions are more dilute; but although the coefficients increase and the nucleations decrease with increasing dilution, nevertheless in case of mineral solutions, for instance, even one ten thousandth per cent. of solute is effective.

Here I may digress by recalling that if the vapor is a hydrocarbon,[2] the fog particles must be relatively large as compared with water under like conditions. Hence the coronas are intensely brilliant and remain normal or white centered in type, even when the nuclei are present in millions per cubic cm. But for the difficulty of keeping these heavy vapors like benzol, carbon-bisulphide, etc , saturated (which may probably be overcome in a revolvable fog chamber), they would offer exceptionally good conditions for the measurement of nucleations. Again the lower order of axial colors which are faint in the steam jet now become vivid and saturated even for short columns. Finally researches on the diffusion[3] of the heavy vapors into (nucleated) air lie within the scope of the coronal method.

10. *Periodicity.*[4] — It is not possible to clean the fog chamber containing graded nuclei in a single exhaustion; even if like the ions the nuclei are fleeting. Large coronas are always evanescent. The evaporation of a fog particle does not therefore restore the original nucleus. The latter

[1] S. C., No. 1651, chap. IV.; No. 1373, chap. V.
[2] S. C., No. 1373, chap. IV.; No. 1651, chap. VI.
[3] S. C., No. 1651, chap. V.
[4] C. P., No. 40, chap. II., VI.

is replaced by a water nucleus. This result has an important bearing on many of the phenomena of condensation. It recurs regularly in the alternation of large and small coronas (superior and inferior as they may be called) obtained in successive exhaustions under conditions of experiment which are otherwise quite identical, filtered air being introduced during the intervening interval after all fog particles have subsided. The efficient nuclei are therefore present, alternately in small and large size and in large and small numbers, respectively, the ratio being often of the order of 8 to 1. Twenty and more alterations have been recorded, but the experiment may be prolonged indefinitely. Non-energized dust-free air above the fog limit, or dust-free air energised by radium or the X-rays,

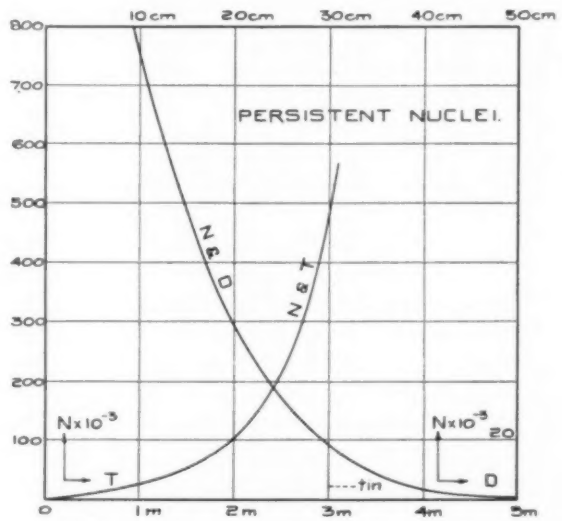

Fig. 4. Generation of persistent nuclei (ordinates, in thousands per cubic centimeter) in the lapse of minutes (abscissas): Curve N and T. Generation of persistent nuclei for the case of different distances (D in centimeters), between the X-ray bulb and the fog-chamber: Curve N and D. The dotted line "tin" shows the number produced through earthed tin plate.

have been tried and the interval between exhaustions may be varied from one to five minutes. Usually relatively high inferior coronas are followed by relatively low superior coronas and low inferior coronas are followed by high superior coronas. Coronas of mean aperture follow others of the same kind so that the periodicity ceases.

The phenomenon is not due to insufficient supersaturation, nor to the occurrence of positive and negative ions, seeing (for example) that in case of non-energised air 12,000 and 90,000 fog particles may be involved. It admits of explanation in all of its details, however, by observing that

the smaller fog particles caught on the smaller nuclei at the end of the exhaustion evaporate into the larger fog particles and become the water nuclei of the second exhaustion. From their relatively large size, these now capture most of the moisture. In the third exhaustion the original nuclei are again available, and so on in succession. The phenomena may be beautifully exhibited by keeping the filter cock all but closed throughout. Fog particles are then continually though slowly evaporated and the coronas of successive exhaustion markedly periodic, showing efficient nucleations, in the ratio of even 15 to 1. Examples will be given in the solution of ions and colloidal nuclei.

11. *Persistent X-ray Nuclei.*[1] — These may be produced by keeping the anticathode close to the fog chamber (say 10 to 50 cm. or more), and subjecting the air to an exposure of from 2–15 minutes. Intense radiation is essential. Wooden or thin glass fog chambers are preferable. An earthed sheet of aluminum may be interposed to guard against inductive action; but this is superfluous. If produced through an earthed sheet of thin tin plate, they are naturally fewer in number. If an elongated fog chamber is used, the coronas are distorted beyond recognition and accompanied by an excessively dense fog. Many of the nuclei are very large and require scarcely any supersaturation to condense water vapor.

To describe the phenomena[2] we may suppose the X-ray bulb to be placed near one end of the fog chamber and distinguish between the near and the far halves of it. For short times of exposure the persistent nuclei are found on the near side only. The coronas are relatively small in size, roundish, decreasing in aperture to a vanishing angular radius from the near end toward the middle of the fog chamber. Beyond this the nuclei are fleeting or too small in size to respond to the given moderate exhaustion, and the far side therefore remains clear. As the time of exposure to the X-radiation is increased from one to ten minutes, the nucleations on the near side become denser and coarser and non-uniform in distribution, vertically as well as horizontally, while the efficient nuclei are found within the fog chamber at continually increasing distances from the bulb, until they eventually fill the chamber without, however, losing their characteristically graded distribution. The growth of coronas from the near to the far side as the time of exposure is increased, when seen through plate glass apparatus immediately after exhaustion, shows a curious succession of forms: they pass from round through oval, spindle-shaped, gourd-shaped (with long serpentine neck), finally to wedge-shaped diffraction patterns. Symmetry about the middle horizontal plane is maintained. Whirling rains and densely stratified

[1] C. P., No. 40, chaps. II., III., VI.
[2] C. P., No. 40, chap. I.

fogs soon follow the condensation, so that the distribution possible for nuclei is unstable for fog particles.

These phenomena must bear on the origin of these nuclei, which are graded in size, decreasing from the near to the far side and increasing from the middle horizontal plane towards the top and bottom (in general towards the walls) of the fog chamber. In fact the forms enumerated are compatible with the diffraction patterns presumable for such gradations. Thus the case is one in which large persistent nuclei either issue from the walls of the chamber by the impact of the X-rays, or in which there is exceptionally rapid growth of nuclei in the field of ionized air adjoining those parts and due to secondary radiation. In case the number of nuclei near the middle plane of symmetry is *apparently* large because these nuclei are nearly of a size and *all* are available for consideration. Near the walls large and small nuclei are intermixed and the former capture practically all the moisture in these regions. Thus there must be many nuclei which fail of capture in the first exhaustion and for this reason the coronas on second exhaustion (without fresh nucleation and exposure to X-rays) are phenomenally large, often corresponding to one-half or to one-third of the number originally present. The large nuclei can not be solutional water nuclei, as they would not then admit of the phenomenon of secondary generation (spontaneous increase in number after radiation ceases) as will presently be explained.

12. *Decay, Exposure and Secondary Generation.*[1]—If we look at the persistent X-ray nucleus as a case in which the rate of production continually exceeds the rate of decay, there will probably be not only a growth of number in the lapse of time of exposure but also of size. In fact the nucleation generated increases at an accelerated rate into indeterminable numbers with the time of exposure for ten minutes or more, barring the invariable loss of efficiency of the X-ray bulb.

The evanescence of these nuclei through the lapse of time is characteristically slow; roughly one-half vanish in ten minutes, four-fifths in eighty minutes. The rate of decay may be estimated as about one hundred times slower than that of the ions, supposing merely for the sake of comparison, that the rates in both cases vary as the square of the nucleation. The coefficient in the terms of seconds would be about 13×10^{-9}.

The accelerated generation of persistent nucleation in the lapse of time, suggests that the nuclei themselves may contribute to this increase. This seems actually to be the case. In other words if the nucleation is observed without cutting off the radiation in one case, and if in the second case the nucleation identically produced is observed at a stated time (1–4 min.) after the radiation has ceased, the number in the latter case (anomalously enough) is an excess. In the first trials the nucleation for

[1] C. P., No. 40, chaps. III., VI.

a lapse of four minutes without radiation is sometimes doubled. The decaying nucleus is thus *virtually* radio-active ; or more simply, the large nuclei if left without interference break into a number (on the average 3) of smaller nuclei. Hence these nuclei can not be water nuclei or it would be difficult to account for their multiplication. The phenomenon vanishes when the radiation is too weak to produce persistent nuclei, therefore when either the X-ray bulb loses efficiency or is too far from the fog chamber. It is always strongest in the first exposure.

13. *Ionization.* — The nucleus as an inert excessively small body often just transcending the order of molecular dimensions, and apt to occur in immense numbers, has an interest of its own ; but this interest is much enhanced, when it is found that by far the greater number of nuclei, even of the persistent type, are initially ionized, or at least carry an electric charge. The cases in which this does not occur have been instanced and are sufficiently exceptional to prove the rule. They probably admit of categorical classification. Apart from these, all nuclei produced by ignition, by high potential, by the X-rays, or even by the comminution of solution, are ionized. So marked is this quality that certain investigators (in particular the younger von Helmholtz), have endeavored to find in the ionization a sufficient cause for the condensation of supersaturated air, or at least an additional tendency to promote it. J. J. Thomson (1888) was the first, however, to adduce theoretical reasons for the condensational activity of the ions.

It is noteworthy that in all of these cases not only is ionization present, but that the ionization and the nucleation in any definite process are proportional quantities even for the case of persistent nuclei. This important result is demonstrable with phosphorous nuclei[1] by passing the charged air at different rates of flow through a tube electrical condenser into the enclosed steam tube, for the cotemperaneous measurement of the ionization and the nucleation ; or again with water nuclei,[2] by conveying the comminuted water from the fog chamber where the nuclei are generated and their number ascertained through the tube condenser specified. In these cases a definite amount of both qualities is producible and may be varied under control of pleasure. Again while the nucleation within reasonable intervals of time is a fixed quantity, the number of electrons per nucleus varies with the incidentals of the experiment ; but for any given adjustment the ratio is constant. Inasmuch as the ionization is subject to much more rapid decay a result of this kind would be anticipated, but detailed investigations on the rates at which the ions and the accompanying persistent nuclei are severally but simultaneously produced and decay and their relations, seem to be of the highest importance.

[1] S. C., No. 1309, chap. V.
[2] S. C., No. 1651, chap. II.

This brings us naturally to a consideration of the fleeting nuclei or the

IONS.

14. *Characterization.*[1] — Let the X-radiation to which dust-free air is exposed be relatively weak, such as is obtained for instance from an X-ray bulb at some distance from the fog chamber, or at closer ranges by using weak radium. The density of ionization then remains below a certain critical value. The nuclei observed on condensation are small as compared with the preceding persistent class, and require a high order of supersaturation (over four-fold), approaching but always definitely below the coronal fog limit of non-energised dust-free air. Wilson showed that condensation begins at a volume expansion of 1.25, increasing thereafter with enormous rapidity. Though this is the same as the rain-like fog limit for air, the corresponding coronal phenomena lie far apart, and the impression to be gained from the charts presently to be shown is very different.

The ions are for the most purposes, instantaneously generated (within a few seconds) by the radiation, so that their number (found throughout by condensation) is practically independent of the time of the exposure, if the radiation is constant. In computing the number of ions one may assume that they are restored faster than they can be removed by exhaustion. They decay in a few seconds after radiation ceases; *i. e.*, to roughly one-half their number in two seconds, to one-fifth in twenty seconds, in the usual way. In other words, if the decay per second is as the square of the nucleation, the coefficient in terms of seconds is about 2×10^{-6}. It is therefore of about the order at which the ions decay (1.5×10^{-6}) when observed by purely electrical methods. If these rates can be shown to be quite identical in simultaneous measurements yet to be made, it would afford the strongest proof possible of the identity of the ions and fleeting nuclei in all relations. I have myself demurred from accepting this view too hastily, for the ions below the maximum dimension which in Wilson's measurements is strikingly constant, are apparently of all gradations of size, the lower limits as the intensity of ionization increases, being continuous with and eventually even overlapping the nuclei of dust-free air. They seem also at times to pass continuously into the persistent nuclei of the preceding section, where the decay of nuclei and of ions are very different things. They are abundantly produced by the gamma rays of radium, which though weak ionizers (contributing but a few per cent. of the ions) are from this point of view strong nucleators. Finally they are stable after solution, *i. e.*, after the evaporation of the fog particles precipitated upon them, while nuclei of otherwise the same properties but free from electric charge may

[1] C. P., No. 40, chaps. III., VI.

be produced by ultra-violet light. The case thus seemed to be one in which the rate of decay soon exceeds the rate of production, so that equilibrium distributions correspond to all of the intensities of radiation by which the ions are produced. Since for a fixed value of fleeting nucleation, the rates of production and decay are the same, we may infer that if the nucleation is 10,000, 100 must be produced per cubic cm. per second; to sustain the nucleation of 100,000, 10,000 must be produced; to sustain one million, two million must be produced.

If we determine the nucleation at two pressure differences near the fog limit of the ionized air, the line so determined may be prolonged to the abscissa and the fog limit roughly ascertained. This is the coronal fog limit, and to it my remarks very largely apply. Below it there usually lies the region of rain-like condensation, which is often largely influenced by the presence of water nuclei or other influences not yet understood. In my earlier work when the intensity of radiating source was steadily increased, the increment of nucleation corresponding to a given drop if pressure varied rapidly, particularly when compared with the fog limit. The successive curves, each taken at constant ionization, are characterized by a rapid increase of slope. The course of the present address will show, however, that this must also result from a rate of exhaustion, increasingly more insufficient as the supersaturation is higher. The rate at which the nucleation increases with the pressure difference (within the limits of efficiency of the apparatus) is about the same for ions and for colloidal nuclei, though the curves lie in widely different regions of supersaturation corresponding to the different sizes of the nuclei. The slopes are preserved even in case of fog chambers of different efficiency. The reason for this is again difficult to conjecture, since the drop in pressure on exhaustion, and not the supersaturation or the volume increase is immediately in question.

15. *Persistence on Solution.*[1] — Fleeting nuclei become persistent after solution, as may be tested by evaporating the fog particles before subsidence is complete, though the rain and some fog particles will naturally drop out. Let the fog chamber be exposed to radiation for a few seconds, and thereafter exhausted below the fog limit of air, as usual. Cut off the radiation at once, rapidly measure the corona and dispel the fog by admitting filtered air. If the chamber is now left without interference for 2 to 5 or more minutes, a second exhaustion to the stated limits will show a secondary corona large relative to the primary corona. In other words, relatively many, 25–50 per cent. of the fleeting nuclei or ions caught in the first fog, have persisted; whereas without condensation, they would have practically vanished within a minute after the radiation ceased. Clearly the ions left in the wake of the evaporation specified, become solutional nuclei, in which the ion behaves as the solute. Such

a nucleus, however small, must be large in comparison with the dissolved ion. A variety of important questions is thus suggested: Does the positive and negative electricity in a case of such solution also persist; if so (from the reduced mobility) there must be slower re-combination. Furthermore if the water nuclei holding positive ions in solution are different in size (as would be probable) from those holding negative ions in solution, there is a possibility of gravitational separation of the fog particles carrying positive and negative charges. The close relation of the whole question of solution with the occurrence of periodicity as described above, has already been instanced, and the occurrence of solution may be verified by the slightly open filter there described (§ 10).

16. *Distributiun of X-radiation.*[1] — Instead of using the X-ray bulb merely as an instrument for the production of ions, we may reverse the case and apply the wooden fog chamber from its extreme perviousness, to an investigation of nuclei-producing radiations in space. This may in a measure be done by the aid of the phosphorescent, photographic, or electrical effects, but it does not follow that the results will be identical. Using the fog chamber with moderate supersaturations the behavior is often astonishing; for when the radiation comes from any distance within a radius of 6 metres (the largest available) from the fog chamber, the fleeting nucleation produced therein is nearly the same, diminishing scarcely 5 per cent. The law of inverse squares would indicate a decrease of 10,000 to 1, within the limits of observation and the phosphorescent screen passes from intense illumination to relative darkness. Again the X-ray tube apparently emits this radiation forward as well as rearward to above 80 per cent. and 16 per cent. of the normal radiation appears even when the current is reversed. The impression gained is that of something extremely penetrating akin to the gamma rays of radium (but this impression is erroneous), and the illusion is accentuated by the fact that the radiation cannot be stopped within 50 per cent. by lead screens placed between bulb and fog chamber near the latter, even for distances of 600 cm. apart. Briefly then, this volume behaves as if the radiant field within were nearly uniform. Such a state of things is very hard to interpret.

Naturally we may explain away much of the difficulty by surrounding the fog chamber with a casket of sheet lead, one or two millimeters thick, in which case the nucleation is reduced to something like ten per cent. of its original value. More than half the radiation is thus derived from secondary sources and enters the broadsides of the fog chamber at right angles or obtusely to the primary radiation. To the eye of the uncovered chamber therefore, and for moderate supersaturations, the walls of the room are aglow with radiation, and no matter where the bulb may be placed (observationally from 6 cm. to 6 meters may intervene between

bulb and chamber), the X-illumination derived from primary and secondary sources is about the same everywhere. Much secondary radiation must always come from the walls of the inevitable fog chamber. But all this does not explain why for moderate supersaturations the sources of secondary radiation should be unlocked about equally independent of the distance of the radiating source, within so large a space. Even if the lead case of the fog chamber is prolonged towards the bulb by a telescoping lead tube one-half of a metre long, the nucleation decreases slower than the inverse first power of the distance.

In recent experiments adapted to secure successively more rapid, and therefore higher supersaturation, the results just sketched were found to need restatement in terms of the exhaustions applied; but to do this effectively it will first be necessary to exhibit the behavior of the colloidal nuclei.

Whether or not the X-ray tube is a source of two kinds of radiation, one of which, gamma-like, is not cumulative and generates the fleeting nuclei of ions from all ranges of distance, while the other generates the persistent nuclei by cumulative action from short ranges, may be suggested for consideration. I should prefer a continuity of action of a single kind of radiation in the way already sketched.

17. *Gamma Rays.*[1] — The final subject to which I shall call your attention in connection with the ionized nuclei is a distinction between the X-rays and the gamma-rays, using in the latter instance about 10 mg. of a weak sample (10,000 ×) enclosed in a thin hermetically sealed aluminum tube. Emanation and alpha rays are thus excluded, while most of the beta rays would be absorbed in the walls of the glass or even in the wood fog chamber. Whether nucleation is markedly produced by gamma rays may then be tested, by enclosing the radium tube in a massive chamber of lead. The results are strikingly confirmatory. The nuclei are thus very largely due to this extremely penetrating radiation, inasmuch as 85 and 70 per cent. of the total number produced in the absence of the lead envelope passed through lead closed walls, one-half and one centimeter thick respectively. Secondary radiation on the outside of the fog chamber is obviously ineffective.

It does not follow, however, that nuclei are produced by the gamma rays directly. The latter more probably induce secondary radiation within the fog chamber to which the nucleation is directly due.

In comparison with the abundant nucleation after the penetration specified, the decrease of the number of nuclei observed when the radium tube is at successively greater distances from the fog chamber, is remarkably large. The ionized nucleation present when the radium tube touches the outside of the chamber falls off to about 17 per cent. for an

[1] C. P., No. 40, chaps. III., VI.

external distance of 50 cm., and to about 10 per cent. for a distance of one meter. Hence, whereas the distance effect in case of the X-rays is small throughout long ranges, it is a very important consideration in case of the gamma rays of impure radium. On the other hand, the latter show a remarkable reserve of a nucleating power even after penetrating a centimeter of lead, whereas the nucleations generated by the X-rays after such penetration are negligible.

Within the fog chamber the distribution of persistent nucleation evoked by the X-rays at close range has already been sketched. When the X-rays act from long ranges the distribution of nuclei within the fog chamber is naturally quite uniform. But the same seems often to be true for radium acting at short distances. Detailed investigation, however, uncovered the complicated nature of the result obtained in this case, for the normal distance effect within is here likely to be obscured by the secondary radiation from the denser and more massive parts of the fog chamber, and by the agencies not yet well understood.

Much else might be said about ions in their condensational aspects, but time is remorseless. I must therefore hasten to consider the last of the groups in the scale of decreasing size, *i. e.*, Wilson's, or the

Colloidal Nuclei of Dust-free Air.

18. *Evidence of the Steam Jet.* — Data bearing on the graded character of colloidal nuclei in dust-free air may be variously obtained, most directly and throughout the widest range, from the behavior of the steam jet.[1] Let a millimeter jet play into a 2-inch tube, actuating a current of air in its own direction. Sky-light passing through it will then be tinged with a definite succession of colors (the axial colors of coronas), varying in a given apparatus with the steam pressure and the temperature of the inflowing air. If these two factors are kept constant, the color is fixed; but if at a given air temperature above 9° C., the pressure is increased, the succession of colors is the same as that obtained from an influx of increasingly nucleated air, at a fixed steam pressure and air temperature. This interpretation may be further verified by the addition of artificial nuclei, observing that the passage of the blues through opaque into the yellows is in the direction of increasing nucleation, or of smaller fog particles. Hence an increase of steam pressure in the absence of efficient foreign nuclei, implies an increase in the number of nuclei available for condensation, or implies an increase of the supersaturation near the jet. If, then, the steam pressure is intensified until the originally clear field, after passing a succession of colors, becomes clear again in consequence of the absence of all condensation, it follows that colloidal-air nuclei in vast numbers and of continually decreasing size must successively become

[1] Bull. U. S. W. B., No. 12, chap. III., 1895.

available for condensation, until the fog particles are too small to be optically discernible. Each particular color corresponds to a group of nuclei characterized by their minimum size. In other words, since any color may be retained indefinitely in the field of view of the steam tube, if its temperature-pressure conditions remain unaltered, groups of nuclei to be reckoned in millions per cubic cm. must suffice for condensation, long before the molecular dimensions are approached. These groups will contain a larger number of particles as smaller particles come within the range of condensation. But even after the yellows of the first order pass into colorless fields, condensation probably still takes place on colloidal molecules, for the phenomena are still variable.

The same results may be deduced, even more cogently, perhaps, from Wilson's observation of the successive disc colors of the coronas, or most certainly from measurements of the succession of coronas in the fog chamber, presently to be examined in detail.

19. *Colloidal Nuclei Soluble.*[1] — Small as they are, the colloidal nuclei admit of solutional enlargement, as may be tested by observing the corresponding fog limits. Let the first exhaustion be made decidedly above the fog limit to obtain a corona of an appreciable size. After evaporating the fog particles by introducing filtered air into the partial vacuum, let the second exhaustion be made decidedly below the fog limit. A large corona, otherwise quite absent, will be observed. Within three minutes about 25 per cent. of the nuclei are found to persist; in ten minutes 5 per cent. are left. Without solution such nuclei are evanescent unless continually reformed.

A much more sensitive method of verifying the same fact consists in observing the depression of the limiting asymptote corresponding, in a given apparatus, to dust-free non-energized air. The more rapid the condensation the higher will be the asymptote and the more marked the lowering due to relatively few water nuclei. If the influx pipe conveying filtered air is in such a case but very slightly opened, the phenomenon of periodicity described above is strikingly in evidence in the successive exhaustions, for the reasons already given. Finally, one may bear in mind that if the act of solution were accompanied by the evolution of electric charge, otherwise inappreciable, the effect attributed here (and in the above similar cases with ions) to solution, may be regarded as evidence of electrical excitation. Specific experimental data are lacking.

Whether or not colloidal molecules are evanescent (as seems probable), they are certainly replaced faster than they can be precipitated. In computing their numbers it is assumed that they are restored to the gas at a more rapid rate than the removal by exhaustion. If different bodies of air are examined after one or more days, when all foreign nuclei must have

[1] C. P., No. 40, chaps. III. and VI.

vanished, the coronas are a maximum for the given conditions. Hence the same conclusion is suggested.

If the filtration is slow through a wide, well-packed, cotton filter, variations of the low rates of filtration are of no consequence. There is no evidence of an addition to the nucleation from this cause. Since the nuclei are not, therefore, dragged through the filter (for which case the coronal aperture would eventually be constant, the enlargement of number being compensated by the effect of volume expansion), they must constitute an essential part of the body of air. If removed in any manner, they are at once re-instated in response to the conditions of molecular equilibrium.

The ionization of atmospheric air is undergoing constant variation. Hence it follows that the efficient nucleation of air must be correspondingly variable; for the larger ions capture relatively much of the moisture. It does not follow, however, that this variation is big enough to be ascertained by the coronal method. Nevertheless it is worth while to examine carefully filtered air for its colloidal nucleation in the lapse of time. Experiments have been in progress in Providence since May 9 of the present year, in which such nucleation is tested several times a day at the highest admissible exhaustion. It is necessary to conduct all of the operations in the same manner, preferably in duplicate apparatus; for the causes of variation are very subtle and each chamber behaves with its own coefficient. However if care be taken to have the stop-cock materially wider than the efflux pipes, so that the predominating resistance to flow shall be here, each chamber will show results which are consistent and quite trustworthy. Using the most sensitive condensation method, *i. e.*, that depending on the depression of the limiting asymptote of non-energized dust-free air, no change of the quality of scrupulously filtered atmospheric air has thus far been detected. This result is the more curious as the ions are usually present to the extent of about 1,000 to the cubic cm. Naturally these would vanish during the slow passage through the filter; but fresh ions should be reproduced within the fog chamber by the same agency which generates them without and which is not believed to be sunlight. Probably, therefore, the coronal method is as yet inadequately sensitive to cope with the variations of the small nucleation specified. At the same time the degree of constancy of the colloidal nucleation of air throughout months of observation is accentuated. After thousands of precipitations this nucleation remains both qualitatively and quantitatively the same.

20. *Natural and Induced Nucleations.*—In conclusion it may repay us to make a complete survey of the nucleations of dust-free air under any conditions. With regard to the method I may recall that the difficulties encountered were enhanced by the need of providing rapid exhaustion, in

case of a fog chamber large enough to measure the coronas and to show the sequence of axial color. The earliest results scarcely captured the maximum of 30,000 nuclei under the extreme exhaustion corresponding to the limiting asymptote. In proportion as the apparatus was perfected, this asymptote was raised, step by step, until nucleations of 500,000 were left in the *exhausted* fog chamber. Probably the asymptote, or more accurately the terminal corona obtained in any given type of apparatus, indicates that the limit of condensing power has been reached. Between the fog limit and the terminal corona, the graph rises in a straight upward sweep; and it is remarkable that the rates at which the nucleations increase with the supersaturation or better with the drop of pressure are about the same between fog limit and asymptote, no matter whether they lie within the region of high supersaturation characteristic of the colloidal nuclei, or in a region of relatively low supersaturation characteristic of highly ionized air. Moreover they are the same in any apparatus, within the limits of its efficiency. In fact even the curve which I have endeavored to reduce to the same scale, from Wilson's disc colors for non-energised dust-free air, and which for the very small apparatus (about 4 cm. in diam.) used, naturally lies in a region of correspondingly low pressure-difference, shows a slope quite in keeping with the other curves. For an imperfect apparatus, on the other hand, the slope terminates abruptly at a lower asymptote and in a region of higher exhaustion. It will be convenient to refer to the nuclei belonging to the slope specified, as representative nuclei.

To obtain the curve for the collodial nuclei of dust free air, it is necessary to wait a week or more, until unknown internal sources of nucleation have spent themselves. Moreover the isolated observations may, with advantage, often be made hours apart; for it is with the exhaustion that the release of spurious internal nuclei occurs.

The air curve passes through the first two cycles of large coronas, terminating beyond the highest green-blue-purple, actually in the stone-blue coronas, the first of the series producible in the fog chamber by any means whatever. It corresponds with the opaques of the steam jet, beyond which, however, there exists another cycle of yellows, to my knowledge quite beyond the reach of the fog chamber. It is not probable that the medium is as yet quite optically inactive after the bluish coronas specified, but merely appears to be so in small thicknesses.

If we turn from the curve of non-energised air to the case of *weak ionization*, such as is produced by impure radium (10,000 ×) or by the X-rays from a distance of 6 meters, we may note in the first place that the coronal fog limit has enormously decreased as compared with its position in dust-free non-energised air. The nuclei are therefore throughout correspondingly larger in size. The nucleation soon rises with an ap-

proach to the characteristic slope referred to, showing that the representative ions lie within a relatively narrow range of sizes, the curve of distribution terminating in a maximum. With increasing exhaustion the nucleation first diminishes to a minimum: Hence to all appearances the ions are now partially destroyed or else materially reduced in size at low

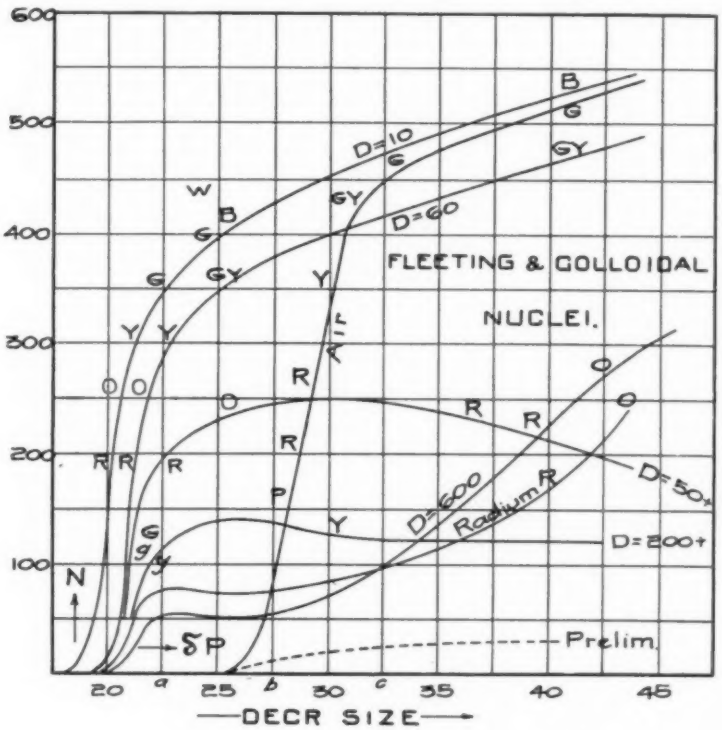

Fig. 5. Nucleation of dust-free air in thousands of nuclei per cubic centimeter, energized or not by weak radium, or by the X-rays from different distances (D in centimeters), as stated. The letters attached to the curves indicate the characteristic colors of the inner field (or its margin) of the largest coronas, the order of colors being $r\ o\ y\ g$ (B). The abscissas show the sudden drop of pressure by which the supersaturation is produced, and the nucleations apply relatively to the given apparatus only. The line marked air shows the behavior of dust-free non-energized air, terminating in the large green coronas. A line drawn from W to g roughly suggests the position of Wilson's data. In a perfect apparatus, supersaturation would increase enormously beyond a; the droplets would be at freezing beyond b. In the given apparatus efficiency probably ceases beyond c, when damp-air is the medium.

pressure, so as to fail of capture even in the higher exhaustions. Beyond the minimum, the final and most interesting stage of variation characteristic of weak ionization may be observed. The nucleation rapidly rises again, eventually to approach the asymptote of dust-free air.

In explanation of this phenomenon, we may agree that further nuclei are destroyed or rendered relatively inefficient by the low pressure until there is a sufficient excess of supersaturation to actually capture the colloidal nuclei of dust-free air more and more fully in the presence of the ions (few in number and small in size) remaining. Possibly the relative number of ions and colloidal nuclei is itself a sufficient reason. Again, if the ions were agglomerated colloidal nuclei, due to the occurrence of a corpuscular kinetic pressure, it would seem plausible that for very weak ionization, the aggregates could not withstand more than low values of exhaustion.

Under *moderate ionization* such as is obtained from the X-ray bulb at a distance of 1 to 2 meters, the fog limit is definitely reduced, showing the presence of an order of larger nuclei; the asymptotes are correspondingly higher and they are reached later (*i. e.*, at higher exhaustion), indicating the presence of smaller nuclei than in the preceding cases, as well. The range of sizes within which the representative nucleations lie is definitely extended in both directions but particularly on the side of the smaller nuclei. The maximum and the minimum are flattened; though destruction of ions still occurs at low pressure.

The new feature of these curves is their failure to rise from the minimum toward the asymptote of dust-free air. It follows that the ions are now present in too large a number even relatively to their reduced sizes at high exhaustion (if this obtains) to leave an excess of supersaturation sufficient to catch the colloidal air nuclei; or from the other point of view, the kinetic ionization pressure is too strong to admit of a sufficient rupture of nuclei even at the lowest pressures applied.

In the comparison of both series of experiments, the occurrence of the intersection of the curves is noteworthy. In other words the nucleation *apparently* produced at high exhaustion by an X-ray bulb at 6 metres from the fog chamber, may be much larger than the nucleation produced from 200, 100 or even 50 cm., due (as we have supposed) to the reappearing efficiency of the colloidal nuclei in the former case. Similar complication surrounds the distance effects at other pressures: but under conditions of very moderate exhaustion, *i. e.*, below the fog limit of filtered air, the distance effect between 50 and 600 cm. remains disproportionately small.

When the ionization is relatively *intense*, as when the anticathode is from 10 to 60 cm. from the thinner sides of the glass fog chamber, the fog limit has decreased somewhat further, showing increased abundance of the larger nuclei; but the slope closely resembles the corresponding case for dust-free air. There is no maximum, but a terminal asymptote, or better a terminal corona of fixed aperture. This corona, which is here the largest obtainable in the fog chamber, is even at the highest ioniza-

tions reached at supersaturations below the coronal fog limit for dust-free air, and long before the apparatus has ceased to function. It is impossible therefore to state whether colloidal nuclei are simultaneously present but inactive or whether their inefficiency is due to actual absence. It thus becomes a problem of great theoretical importance in its bearing on this subject to determine how the precipitated supersaturation is distributed among groups of nuclei of different sizes.

21. *Radiant Fields.* — The occurrence of a succession of groups of colloidal nuclei of (let us say for simplicity) continuously decreasing size and continuously increasing number is suggestive; for each group is essential in the given natural but otherwise unknown environment. They are at once restored if withdrawn. These conditions may be imitated or varied artificially by approaching the radium tube at different distances from the fog chamber, in which case the efficient nucleation will for weak radiation usually decrease, as the intervening distances are smaller.

Furthermore in the presence of radium the character of the phenomenon is the same, only the nuclei are throughout larger. Withdrawn by precipitation they are at once restored. They are an essential part of air in the new (radiant) environment and the nuclei are again graded.

It is natural to compare the particular nuclear status introduced in the latter case by a particular kind of radiation (gamma rays), with a former case of dust-free air in the absence of recognized radiation. In other words, if we abstract from the details of the mechanism which are unknown for the colloidal nuclei, chemical agglomeration might be considered referable to some radiant field, unknown but otherwise essentially alike in kind, to the much coarser nucleations observed on exposure to the known radiant field. The effect of radium, however distant, is virtually an increase of size of the efficient air nuclei and a decrease of their number. Hence if we were to fancy that the colloidal nucleation of air responds to its own radiant environment, this would have to be special in kind.

Recently I have made similar tentative inquiries, as to whether the ions and persistent nuclei might not be regarded as colloidal nuclei aggregated by kinetic pressure, corpuscular or undulatory. For in view of the occurrence of pronounced secondary action within the fog chamber, the radiation at any point must be considered as sufficiently the same in all directions, to be equivalent to a Lesage medium. It is then possible to account for the nucleation in any ionized field, for fleeting and persistent nuclei, for condensational differences of positive and negative ions, for fleeting nuclei otherwise identical but respectively charged and uncharged, for the destructive effect of low pressure and the counteraction in strong ionized fields, for electrical differences in the effect of ultra-violet light and of X-rays, etc., with a single straightforward hypothesis.

While such a view may be worth a statement, it would at the outset encounter very determined opposition; and the distinctive or differentiating evidence to sustain it, is uncertain. Briefly, if we admit that with ions sufficiently large and sufficiently numerous relatively speaking, the colloidal nuclei are virtually non-existent (so far as the fog chamber is concerned), since the former capture all the available moisture, most of the phenomena of nucleation admit of interpretation, and additional hypotheses, however alluring, are not called for. Moreover so long as the representative colloidal nuclei are definitely smaller than the smaller ions, even in the strongest electrical field; in other words if what may be called the shattering action of strong fields always fails to reveal ionized nuclei as small as the representative colloidal nuclei, the special interpretation is not warranted. On any hypothesis, it nevertheless remains hard to conjecture, why an ion regarded as a loose aggregate either of molecules or of colloidal nuclei, behaves as a perfectly stable body on solution.

In conclusion, if we asked what is the most important outcome of researches of the present character, I should refer to the appearances obtained, indicating that a gas, or at least a moist gas, far from being a uniform system, behaves like an assemblage of nuclei[1] which decrease in size and increase in number as the molecular dimension is approached. Every group of nuclei is none the less a structurally essential part of the gas and (be the number of groups few or many) at once restored if withdrawn; while the molecule itself is distinguished among the many nuclei of its own kind, by the maximum frequency of occurrence.

Before closing let me acknowledge that I have dwelt all too briefly and with entirely inadequate enthusiasm on the work of my colleagues both at home and abroad: but I felt justified in taking the opportunity of this address to bring together in a connected way, the papers which from time to time I have had the honor of laying before this Society.

BROWN UNIVERSITY, PROVIDENCE, R. I.

[1] If for instance the colloidal nuclei were attributed to dissociations and associations due to the sudden drop of pressure (with which in fact there is a close connection), there would be no reason for the recurrence of the same phenomenon with the steam jet, where moreover high temperatures replace the low ones of the fog chamber. A mechanism of ions, dwindling at decreasing pressures in the midst of molecules, is perhaps more promising.

The Electrical Production of Ozone.[1]

By Arthur W. Ewell.

PROFESSOR WARBURG and the writer have quite exhaustively studied the electrical production of ozone with point and plate electrodes.[2] No such study of the electrical production of ozone with an alternating current and plate electrodes separated by a dielectric has been published hitherto except for papers by Dr. A. W. Gray[3] which cover a very limited field.

During the past year the writer has conducted quite exhaustive experiments working with this type of electrodes. Current, gas velocity, form, and distance between electrodes, and dielectric were varied and for each the yield in grams per coulomb and per kilo-watt hour was determined. To briefly summarize the results: the yield per coulomb was found quite independent of the dielectric and greater the higher the gas velocity. Owing to increasing deozganization the yield increased with the current to a maximum and decreased. Narrow, bare, electrodes were most efficient. The yield per kilo-watt hour was greatest for a polar distance of a few millimeters. This type of electrodes proved far more efficient than the point and plate and than other minor types.

The Absorption of Alpha Rays in Gases and Vapors.[1]

By E. P. Adams.

THE method employed to determine the absorption of various gases and vapors for the alpha rays consists in measuring the maximum distance between a source of alpha rays and a zinc sulphide screen at which the scintillations can be seen. The source of the alpha rays is a bismuth plate rendered active by one of the radioactive substances present in the mineral carnotite — probably polonium. It is found that for any given gas or vapor the product of this maximum distance by the pressure is nearly a constant. In many cases this product increases somewhat with increasing pressure. The average value of this product is determined for a number of gases and vapors, and it is found that this product varies inversely as the sum of the square roots of the atomic weights of the atoms which make up the molecules of the substances under obser-

[1] Abstract of a paper presented at the New York meeting of the Physical Society, Dec. 29–30, 1905.

[2] Annalen der Physik., 17, 1905, p. 1.

[3] Physical Review, November, 1904, p. 347.

vation. A similar relation was found by Bragg and Kleeman for the so-called "stopping power" of various substances for the alpha rays from radium, when measured by their ionizing effect. A number of gases and vapors, ranging in complexity from hydrogen to nickel carbonyl have been examined, with only two or three cases where the deviations seem to lie outside the limits of experimental error.

DIFFERENTIAL TEMPERATURE RECORDS IN METEOROLOGICAL WORK.[1]

BY C. H. MCLEOD AND H. T. BARNES.

IN 1897 the British Association made a grant of £50 towards an investigation of the changes in temperature due to the differences in altitude at Montreal. In the summer of 1899 an electric recording apparatus was installed in the McGill College Observatory, and arranged to read differences in temperature between the summit of Mount Royal, and the Observatory grounds. Platinum resistance thermometers were placed in the two places and connected in the first instance by No. 14 copper electric light leads. On account of the length of the run, nearly a mile, the insulation was not sufficiently good in wet weather to obtain satisfactory traces.

In the summer of 1903 a special gift from Sir Wm. Macdonald made it possible to erect a lead-covered cable, and efforts to obtain satisfactory traces were resumed with a fair amount of success. Continuous traces have been obtained for two years with but two interruptions in that time, for a few months each in the summer, and with the exception of the two stoppages, both of which were traceable to wanton interference with the cable, the cable has proved satisfactory for the work.

The thermometer on the summit of the mountain is placed on a tower 47 feet above the ground, and 800 feet above sea level, and is enclosed in a single screen cage. The thermometer in the observatory grounds is 4 feet above the surface of the soil and 180 feet above sea level, and is enclosed in a double screen cage. The difference in level of the two thermometers is seen to be 620 feet, with the Mountain thermometer in a direction approximately northwest from that on the observatory grounds. The horizontal distance is 3,300 feet and the actual length of the connecting cable is 4,100 feet including four No. 16 copper wires insulated by the ordinary telephone paper covering.

An inspection of the many traces which have been obtained shows that the temperature of the higher station is normally below that at the lower.

[1] Abstract of a paper presented at the New York meeting of the Physical Society, Dec. 29–30, 1905.

The amount of the difference reached as much as 25 degrees Fahrenheit during the winter of 1903–4 on one or two occasions, but the average difference was from 4 to 8 degrees. The traces for the following winter did not show such great variations, the greatest being 7 degrees below the temperature of the lower station.

The most interesting feature of the records is in the manner in which an approaching change in the general temperature conditions can be observed several hours ahead on the higher thermometer. Thus the position of the trace relative to the zero, as well as whether it is rising or falling, is of the greatest importance in determining the temperature that will prevail at the lower station 10 or 12 hours later.

We have accumulated as much evidence as is possible without further experience, but so far as daily indications are concerned we have learnt to rely on the differential temperature trace and have seldom found it at fault. It is possible that the extent and duration of the difference may make it possible to form estimates for much longer periods ahead, but it will be necessary to compare a considerable number of yearly traces before definite information can be given on that point.

McGILL COLLEGE OBSERVATORY,
MACDONALD PHYSICS BUILDING,
December 16, 1905.

THE RELATIVE CONDUCTIVITIES IMPARTED TO A FLAME OF ILLUMINATING GAS BY THE VAPORS OF THE SALTS OF THE ALKALI METALS.[1]

BY F. L. TUFTS.

THE paper presented the results of measurements made on the relative conductivities imparted to the various types of flames of illuminating gas by the different salts of the alkali metals. The method employed was that described in a previous paper.[2] The following is a summary of the results obtained.

The supposed difference in conductivity imparted to a flame by the oxysalts and the halloid salts at high concentrations, found by Smithels, Dawson, and Wilson,[3] was shown by the experiments to be due to the different action of these salts at the platinum electrodes. When the electrode effect was eliminated by using separate electrode flames, the conductivity imparted to the connecting flame by the vapor of an equiva-

[1] Abstract of a paper presented at the New York meeting of the Physical Society, Dec. 28–30, 1905.

[2] PHYSICAL REVIEW, Vol. XX., page 186.

[3] Phil. Trans., 193 A, p. 105.

lent solution of KNO_3 and of KCl respectively, was found to be the same, although the concentration of the vapor in the connecting flame was so great that when the platinum electrodes were placed in this flame the current due to the KNO_3 vapor was eight times the current due to the KCl vapor, the impressed E.M.F. being two volts.

The relative conductivities imparted to a flame by equal quantities of the spray from equivalent solutions of the salts of Li, Na, and K were found to be very different for the different types of flame. When the rate of supply of gas was greatly in excess of the rate of supply of air to the burner, giving a flame rich in carbon luminosity, the relative conductivities were as follows:

$$\text{Li} = 1 \qquad \text{Na} = 6 \qquad \text{K} = 35.$$

When the rate of supply of air was much in excess of the rate of supply of gas, giving a very oxidizing Bunsen flame, the relative conductivities were

$$\text{Li} = 1 \qquad \text{Na} = 6 \qquad \text{K} = 9.$$

In a flame of the first type in which the only air supplied to the burner was that blown through the atomizer, it was found that for all the salts investigated, the salt conductivity imparted to the flame was directly proportional to the rate of supply of the mixture of air and spray from the atomizer.

If we assume that a necessary condition for the formation of salt ions is the collision in the flame between oxygen and salt particles, then the rate of production of such ions, other conditions remaining the same, would vary directly as the product of the number of salt particles (n_1) into the number of air particles (n_2). Or, the rate of production of salt ions in the flame would vary directly as the square of the rate of supply of air and spray. Applying the relation which is found to hold in other cases of ionization in gases, viz.:

$$an^2 = q$$

where a is the coefficient of recombination of ions within the flame, n the number of free salt ions in the flame, and q the rate of formation of such ions. Since q is proportional to $n_1 n_2$ we may write,

$$an^2 = n_1 n_2,$$

or

$$n = N/\sqrt{a},$$

where N is proportional to the rate of supply of air and spray to the flame. Since the salt conductivity of the flame is directly proportional to the number of free salt ions (n), it follows that it would be directly

proportional to the rate of supply of air and spray (N). The measurements showed this to be the case.

The above deduction would only hold strictly true in case there were no recombination between salt ions and flame ions within the flame. The fact that one gets such consistent results by treating the flame conductivity and the salt conductivity as simple additive quantities would indicate that within the flame there is no recombination between the two kinds of ions.

The Optical Properties of Exceedingly Thin Films.[1]

By Wm. B. Cartmel.

THIS work which was mostly done during the summer of 1905 was undertaken to determine the behavior with regard to light of films whose thickness was very much less than a wave-length. I experimented upon five fuchsine films varying in thickness from about a wave-length to $\frac{1}{600}$ of a wave-length. Wishing to determine the thickness by other than optical means I dissolved films whose area was known, in a definite quantity of alcohol and knowing the specific gravity of solid fuchsine, I could determine from the concentration the amount of fuchsine in solution and hence the thickness of the film.

The th nnest films had scarcely a measurable absorption for any color, but the amount of light reflected could be measured with a considerable degree of precision. The changes of phase produced by the thick films I have already measured, and I am engaged in measuring this from the thinner films.

The paper contains also a theoretical discussion of the reflection and refraction by thin films.

On the Velocity of Sound in Gases at Low Temperatures and the Ratio of the Specific Heats.[1]

By S. R. Cook.

THE purpose of the experiments set forth in this paper was primarily to determine the velocity of sound in air and oxygen at temperatures at which these gases would be in their vapor condition. Greely had made a series of experiments on the velocity of sound at temperature as low as $-79°$ F. Within the limit of accuracy of his experiments,

[1] Abstract of a paper presented at the New York meeting of the Physical Society, Dec. 29–30, 1905.

Greely found that the velocity of sound decreased 60.3 cm. per degree centigrade and that the ratio of the specific heats was constant.

Withkowski, Stevens, Kalahne and Lonncke, all have made observations or deductions on the variation of the specific heats, with temperature and pressure, and have come to different conclusions, when the variation was carried far enough. The paper deals only with the variation of the ratio of the specific heats with the variation of temperature.

The velocity of sound was measured, at the temperature of liquid air, by the usual Kundt method. The comparison sound tube was introduced into a Dewar bulb, filled with liquid air.

The apparatus was so arranged that the direct ratio of the wave-lengths could be measured, and the ratio of the specific heat computed from the formula,

$$\nu = \nu' \rho \left(\frac{\lambda}{\lambda'}\right),$$

where ν and ν' and λ and λ' are the ratios of the specific heats, and the wave-lengths of sound, respectively, in the gas at two different temperatures; and ρ is the relative density of the gas at the respective temperatures.

A series of measurements were made on air at the temperature of liquid air, and it was shown that the velocity decreased more than could be accounted for by the relative variation in the density, in accordance with the Boyle-Gay Lussac-Avagadro law.

Oxygen, at the temperature of liquid air, was below its critical temperature, at atmospheric pressure, and the measurements were made at reduced pressure. The same tendency was observed in oxygen as in air.

When the ratio of the specific heats was determined from the simple formula above, the measurements showed, that, when these gases were in their vapor state, the ratio of the specific heats decreased slightly. The ratio of the internal to the external energy of the molecule was also computed from the data.

The simple formula for connecting the ratio of the specific heat with the ratio of energies is,

$$\beta + 1 = \frac{2}{3} \frac{1}{\nu - 1},$$

where β is the ratio of the internal to the external energies of the molecules. As ν decreased at low temperature, β increased correspondingly. Formulæ were deduced by the application of the characteristic equation of Clausius and also of Van der Waals; and applied to the computation of β. The corrections were very small, much less in fact than the probable error in the determination of β.

A New Determination of the E.M.F. of the Clark and Cadmium Standard Cells by Means of an Absolute Electrodynamometer.[1]

By K. E. Guthe.

THE method employed in this investigation was practically the same as the one described by Professor Patterson and the author a few years ago; but special attention was paid to an elimination of all errors which might possibly amount to more than one in ten thousand.

The electrodynamometer consisted of coils wound with a single layer of wire and of dimensions, first proposed by A. Gray, such that the length and radius are in the ratio of $\sqrt{3}$: 1 to each other. The frame for the stationary coil was a hollow plaster of Paris cylinder, soaked in paraffine and very accurately turned on a boring mill. Its average diameter was determined by means of a large caliper of nickel iron and its coefficient of expansion taken into account in the calculations. The cylinder was wound with 872 turns of wire consisting of two separate coils, the turns of one being wound between those of the other, so that alternate wires belonged to different coils. This enabled us to measure the insulation resistance (40 megohms) of the whole apparatus after completion. The diameter of the stationary coil was close to 50 cm. and the length nearly 43.3 cm. The irregularity of the winding which was a little closer at the center necessitated a correction of somewhat more than one in one thousand.

In order to test the reliability of the results two movable coils of different dimensions were constructed, the larger having a diameter of 10 cm., the smaller of 7.5 cm. The porcelain cylinders, used as frames, were wound with 109 and 83 turns respectively, of bare copper ribbon, and the average diameters were measured by means of end comparators, reading to 0.001 mm.

The current was led into the movable coil through mercury cups and it was found necessary to slightly agitate the mercury during the observations in order to eliminate the disturbing effect of surface tension. The coils were carefully centered with their axes parallel and then the movable coil turned into position by twisting the torsion head by 90 degrees. Angles in the neighborhood of 90 degrees could be determined by means of a silvered glass cube whose angles had been measured accurately.

All materials used in the instrument were tested for magnetic permeability by means of a device, consisting of two induction coils, the induced electromotive forces in the secondaries being opposed to each other. The

[1] Abstract of a paper read at the meeting of the American Physical Society, December 29–30, 1905.

material to be tested could be introduced inside of the primary of either coil. The permeability of plaster of Paris and porcelain differed not more than one in 100,000 from that of air.

It was decided after several unsuccessful trials with fused quartz, steel, platinum-iridium, carbon and other substances to use for a suspension a twelve year old phosphor bronze wire which showed a rather constant modulus of torsion and little elastic after-effect.

The modulus of torsion of the wire was determined by vibrating, suspended from it, gold plated cylinders of Tobin bronze whose masses and dimensions were accurately known. Two sets, each consisting of two cylinders of the same mass, but different shape, were used; the masses of the heavier set being equal to that of the larger movable coil and the cylinders of the other set weighing the same as the smaller coil. It was shown that the modulus of torsion of the suspension can be determined with sufficient accuracy from vibration experiments made with these cylinders and that it will keep constant enough during the time necessary for electrical determinations.

The standard cells were obtained through the kindness of Professors Carhart and Hulett. They were kept during the last weeks of the investigation within 0°.01 C. at 25° C. by means of a thermostat.

The cells were mostly cadmium cells, with electrolytically prepared mercurous sulfate (*E*, *F* and *O* series). Two cadmium cells contained chemically prepared mercurous sulfate (K_{10} and C_8) and three Clark cell (*R* series) were set up with electrolytic mercurous sulfate. The *F* series in which the mercurous salt was precipitated in an acid of concentration larger than molecular, the electromotive force is 0.00006 volt below that of the *E* and *O* series, and 0.00030 volt below that of the *C* series.

The electrical determinations consisted in sending the current flowing throw the electrodynamometer and balancing a torsion of the suspension equal to 90 degrees, through standard resistances and comparing the potential difference produced at their terminals with the electromotive force of the standard cells by means of a calibrated potentiometer. The elastic after-effect due to the twisting of the wire was taken into account.

The absolute value of the current was calculated from the formula

$$I^2 = \frac{\pi}{2} \frac{\tau}{AC}$$

where τ is the torsional moment for unit angle of the suspension, *C* the magnetic field in the center of the stationary coil, and *A* the effective area of the movable coil. In order to eliminate the effect of the earth's magnetic field and the possible influence of the lead wires it is necessary to take the geometric mean of four currents, obtained by reversing the current through the whole apparatus and for each of these two cases reversing the current in the movable coil.

Seven complete determinations were made, three with the smaller and four with the larger coil. As reference standard an unsaturated Weston cell was used and its electromotive force at 21° C., was found, as shown in the table.

A. With smaller movable coil:	
Exp. 1.	1.01889 volts.
2.	1.01877 volts.
3.	1.01887 volts.
B. With larger movable coil:	
Exp. 4.	1.01886 volts.
5.	1.01885 volts.
6.	1.01887 volts.
7.	1.01880 volts.

From the comparison by means of the potentiometer method the electromotive force of the standard cells at 25° C., was found to be:

E.M.F. of the *F* cells (electrolytic) = 1.01827 volts.
E and *O* cells (electrolytic) = 1.01833 volts.
C cells (chemical) = 1.01857 volts.
R cells (electrolytic) = 1.42040 volts.

Reducing to 20° C., by assuming the temperature coefficient for the electrolytic cells to be the value accepted for those with chemically prepared mercurous sulphate, we find

E.M.F. of the *F* series at 20° C. = 1.01847 volts.
E.M.F. of the *C* series at 20° C. = 1.01877 volts.
and E.M.F. of the Clark cells at 15° C. = 1.43295 volts.

The electrochemical equivalent of silver, expressed by the author some time ago in terms of the electromotive force of a Weston cell, may now be calculated in absolute measure, since the cell used in the former work with the coulometer could be compared directly with the reference standard of this research. For a porous cup silver coulometer the electrochemical equivalent of silver, thus found, is

1.11774 mg. per coulomb.

Experiments on Resonance in Wireless Telegraph Circuits.[1]

By George W. Pierce.

THIS paper reports a continuation of experiments on the conditions for resonance in wireless telegraph circuits. Both the electromagnetically-connected type and the direct-connected type of circuits were studied, and a comparison of the two was made with respect to sharpness of resonance and the intensity of the signals received. The compari-

[1] Abstract of a paper presented at the New York Meeting of the American Physical Society, December 29, 1905.

sons were made by measurements of the energy at the receiving station by methods described in the author's previous papers.

With the *electromagnetically-connected* circuits the "coefficient of coupling" of the circuits was varied by varying the mutual inductance between the two parts of both the sending and the receiving stations. The effect of such variation was found approximately to accord with the theory of inductive circuits; namely, with a decrease of the coefficient of coupling the capacity-hyperbola, described in the previous papers, approached its asymptotes, and the resonance became sharper. In an extreme case where the coefficient of coupling at the receiving station was .071 the resonance was so sharp that the energy received dropped to one half for a change of period of one and one half per cent.

With the *direct-coupled type of circuits* several methods of tuning were employed. In all cases the resonance was far less sharp than with the inductively connected circuits. For certain methods of tuning the direct-coupled type of circuit was shown to be a special case of the electromagnetically connected system.

In regard to the relation between the amount of energy received and the height of receiving antenna, the following approximate laws were obtained:

With a constant sending circuit and a constant source of waves,

I. *The current received in a direct-couple receiving circuit brought to resonance by a capacity in shunt is proportional to the square of the height of the receiving antenna.*

II. *When the receiving circuit is brought to resonance by an inductance in series with the instrument, the current in the receiving circuit is proportional to the height of the receiving antenna.*

These results are interesting in that they show entirely different laws for different methods of tuning. Therefore, the relation of height of mast to the distance to which signals may be sent (Marconi's Law, Braun's Law, etc.) will be dependent on the method employed in bringing the sending and receiving stations to resonance.

The paper also gives experiments on artificial grounds with a confirmation of the *image-theory* of the action of the ground. In the opinion of the author it is easy to construct an artificial ground superior to such natural grounds as may be effected by burying plates of metal in the earth.

Wave-lengths from 500 to 150 meters were employed in these experiments.

Longitudinal Vibrations Analogous to those of a Violin String.[1]

By Harvey N. Davis.

THIS work was originally undertaken as the first step in an investigation of the effect of vibration on magnetic quality, an experiment in which it is desirable to maintain, in a steel wire, a steady state of vibration whose character and intensity can be fully determined and easily controlled. This has been accomplished by means of a mechanically operated rubbing-wheel, and a study of the resulting longitudinal vibrations has shown them to be identical in character with the transverse vibrations of a violin string. This fact gives them a considerable interest, quite apart from the specific use which is presently to be made of them, in that there is here presented a unique and exceedingly detailed experimental illustration of the parallelism between longitudinal and transverse vibrations which the mathematics of the subject predicts. Practically everything that has been observed for the violin string can be reproduced in the longitudinal case.

In two respects the present paper goes beyond the work of previous observers. In the first place, the fact that a given state of vibration can be kept up indefinitely and can be reproduced at will, has made it possible, for the first time, to measure amplitudes under conditions which are accurately known. This has resulted in a good quantitative verification of the established theory, and especially of the law connecting amplitude with bowing speed. The second of the contributions of the paper relates to the problem of solving the differential equation of vibrating strings subject to the peculiar kind of boundary conditions which the theory of the bowed string demands. The desired solution can be obtained in the form of a Fourier's series without difficulty, as Helmholtz first showed; but it is extremely difficult even in the simplest cases, and impossible in any but the simplest cases, to obtain from such a series any information as to the configurations of the string itself as it vibrates, or as to the nature of the motion of its individual points. To avoid this difficulty the author has devised a simple graphical method which will give this information in any case which the present state of the theory of bowed strings presents. Even in those simple cases which can be handled by the older method, the saving of time and of energy is so great as to be a matter of considerable importance to one

[1] Abstract of a paper presented at the New York meeting of the Physical Society, December, 1905. The paper will be published in the Proceedings of the American Academy of Arts and Sciences, and in the annual volume of the Jefferson Physical Laboratory of Harvard University.

working in the subject. It is possible that this part of the paper will have some interest for the pure mathematician, for it is rather unusual that graphics should be able to give, not simply an approximate, but an exact and rigorous answer to a question which analysis is, as yet, unable to solve.

MAGNETIC AND ELECTRIC DEFLECTION OF THE α RAYS FROM RADIUM.[1]

BY E. RUTHERFORD.

THIS paper contains a preliminary account of experiments made to determine with accuracy the ratio e/m of the α particles projected from radium. The α rays from radium are complex and consist of particles projected with very different velocities. Such a source of rays is not suitable for accurate measurement, as the rays are unequally deflected in electric and magnetic fields.

This difficulty was overcome by using an active wire exposed for some hours to the radium emanation as a source of rays. Fifteen minutes after removal, radium *A* has been almost completely transformed, and the activity is then due almost entirely to radium *C*. Previous experiments by the author (Phil. Mag., July, 1905) have shown that such an active wire serves as a homogeneous source of α rays. The layer of active matter on the wire is extremely thin, and the α particles are all projected from the wire at the same speed.

The magnetic deflection of the α rays was measured by a method similar to that described in a previous paper (loc. cit.). The electric deflection was determined by the photographic method. The rays passed between two parallel plates 3.75 cm. long and .21 mm. apart. A photographic plate was placed about 4 cm. above the plates. The apparatus was then exhausted by a mercury pump, and a known voltage applied between the plates. The active wire was placed outside the apparatus, the rays entering the vessel through a thin mica screen of known thickness. The electric field was reversed at intervals. For weak fields, the narrow trace of the rays on the plates was first broadened; with stronger fields, the single band broke into two, each narrower than the normal width of the band without an electric field. The outside edges of the bands were clearly defined, and the distance between the outer edges could be readily measured.

In this arrangement, the parallel plates served to determine the width of the pencil of rays, as well as to apply the electric field. Since the plates were close together, a field corresponding to 20,000 volts per cm.

[1] Communicated to the American Physical Society, December 29, 1905.

could be obtained with 400 volts between the plates, without any danger of a discharge, even if the vacuum were not very good.

From the distance between the outside edges of the two bands, the value of mv^2/e could be calculated. The value of mv/e was determined in the magnetic experiment by measuring the curvature of the path of the rays after passing through the same thickness of mica as in the electric experiment.

The determinations of e/m and v for different strengths of electric and magnetic fields were very concordant. The values of e/m in the different experiments lay between 5.0×10^3 and 5.2×10^3. A separate experiment showed that the value of e/m was unaltered by passing the rays through the mica screen.

The initial velocity of projection of the rays from radium *C* is very nearly 2×10^9 cm. per second.

The writer originally obtained by the electric method a value of e/m for radium rays of 6.5×10^3; Des Coudres by the photographic method found a value 6.3×10^3, while Mackenzie recently obtained a value of 4.7×10^3. These experimenters all used radium in radioactive equilibrium as a source of α rays. The rays were non-homogeneous, and it was consequently not easy to obtain an accurate value of e/m.

Since the value of e/m for the hydrogen atom in the electrolysis of water is about 10^4, the present results show that, within the limit of experimental error, the apparent mass of the α particle from radium *C* is twice that of the hydrogen atom.

The question whether the α particle is a molecule of hydrogen, an atom of helium, or a helium molecule carrying twice the ionic charge, was discussed. It is not at present possible to decide definitely between these possibilities. Further experiments are in progress to determine the value of e/m for the α particles from the other radium products and from thorium and actinium.

Some Properties of the α Rays from Radium. II.[1]

By E. Rutherford.

In the Philosophical Magazine (July, 1905), the author showed that the α particles emitted from a thin film of radium *C*, obtained on a wire by exposure to the radium emanation, decreased in velocity in their passage through matter. When the α particles from radium *C* had been reduced to a velocity of about 60 per cent. of their initial velocity, the photographic effect produced by them was relatively very small.

The velocity was deduced from measurements of the deflection of a

[1] Communicated to the American Physical Society, December 29, 1905.

pencil of the α rays in a strong magnetic field, using the photographic method. The results confirmed the essential points of the theory of Bragg and Kleeman of the nature of the absorption of the α rays by matter. The rays from radium are complex and consist of four sets of α rays from the four α ray products, each set of rays being initially projected with a definite but different velocity.

In a recent paper, Becquerel (Comptes Rendus, Sept., 1905), has taken exception to these views. He states that the α rays from radium are homogeneous, and that their velocity is not reduced by their passage through matter, and concludes that the theory of Bragg and Kleeman is incorrect.

In support of his views, Becquerel describes an experiment in which the trace of the α rays from a thick layer of radium was not altered by placing absorbing screens over the radium.

The author showed that the result obtained by Becquerel is a necessary consequence of the view that the rays are complex, and does not in any way invalidate the conclusions of Bragg and Kleeman and Rutherford. The outside edge of the trace of the pencil of rays on a photographic plate, when exposed in a magnetic field, is due to the α particles which are just able to produce an appreciable effect on a photographic plate. When a screen is placed over the radium, the velocity of all the particles is reduced, but, as before, the outside edge of the trace will be produced by rays which, after emerging from the screen, have the same velocity as in the first case. The deflection in a magnetic field will consequently be unaltered, and there will be no apparent displacement of the trace of the rays, although the velocities of the α particles as a whole are reduced in their passage through matter.

The inside edge of the trace should be slightly altered but this effect would be too small to detect experimentally under the conditions of the experiment of Becquerel.

It was also shown that the α rays from a thick layer of radium are deflected to unequal extents by a magnetic field. This dispersion of the rays in a magnetic field shows that the α particles are expelled from radium over a wide range of velocity. The position taken by Becquerel, viz., that the α rays are all projected at the same speed, is untenable.

Becquerel observed that the radius of curvature of a pencil of rays emitted from radium was not constant but increased with distance from the source. The explanation of this effect has been given previously by Bragg, and has been shown to be a necessary consequence of the complexity of the α rays. The assumption made by Becquerel that the ratio e/m decreases with distance from the source of rays is unnecessary. In addition, the author showed that the magnetic deflexion of the α rays from radium C increased when the rays passed through air instead of a

vacuum. According to the views of Becquerel, the amount of deflexion of the α rays under such conditions should be reduced by their passage through air.

The results in general completely support the theory of Bragg and Kleeman that the α rays from radium decrease in velocity in their passage through matter, and disprove in every particular the theories proposed by Becquerel.

On the Use of Centrifugal Force in Soil Investigations.[1]

By Lyman J. Briggs.

CENTRIFUGAL force can be employed with advantage in the following laboratory investigations of soils:

1. The study of the retentive power of different soil types for moisture. The moist soil is placed in a perforated cup and subjected to a known centrifugal force, by which the moisture content is reduced until it is in equilibrium with the force employed. It logically follows that two soils whose moisture contents have thus been brought into equilibrium with the same force should, when placed in contact, be in capillary equilibrium. The method thus enables us to determine the moisture equivalents of different soil types, which it is essential to know before the moisture contents of two soils under field or laboratory conditions can be rationally compared.

2. The study of the rate of movement and the final distribution of moisture in a column of soil when acted upon by a known force. In this case the tube containing the moist soil is mounted radially on a shaft revolving at a known rate. The method gives a means of determining the moisture gradient necessary to maintain equilibrium against a uniform force gradient. By the arrangement of the apparatus so that water can be supplied at a definite rate, the moisture gradient necessary to maintain a steady flow of known amount under the influence of a given force gradient can be determined. The direction and rate of movement of soil moisture under field conditions can then be determined from a study of the moisture distribution in the field. These methods have not yet been tried experimentally.

3. The study of the composition and concentration of the soil solution. A part of the soil moisture with the substances it holds in solution can be removed by centrifugal force without changing, so far as we have been able to determine, the composition or concentration of the soil solution. This method possesses obvious advantages over the excess-solvent

[1] Abstract of a paper presented at the New York meeting of the Physical Society, December 29–30, 1905.

methods, in which the relatively large amounts of solvent used affect the equilibrium of the soil solution.

4. The study of the mechanical composition of the soil. The mechanical composition is found by separating the soil grains into arbitrary groups according to size, by taking advantage of the different rates of subsidence of the soil particles in water. The use of centrifugal force is of much assistance in hastening the subsidence.

AN ELECTRICALLY CONTROLLED THERMOSTAT OPERABLE AT ROOM TEMPERATURES.[1]

BY LYMAN J. BRIGGS.

MOST thermostats heretofore described have been designed to operate either above the maximum or below the minimum room temperature, so that their regulation could be effected by the control of either a heating or a cooling system. The form described in this paper will operate satisfactorily, even though the temperature of the room may be constantly fluctuating above and below the temperature of the thermostat. The heating is effected by an electric heater, and the cooling by tap-water or ice-water according to the requirements, the flow being regulated by an electrically controlled valve.

Acetone, which has a cubical coefficient of expansion of about two fifths that of air, is used in the temperature regulator. The expansion of this liquid controls the height of a mercurial column *in vacuo*. Two small platinum wires are sealed into the glass tube containing the mercurial column at a distance of about one centimeter above the mean barometric height, one wire being about one millimeter above the other. The relay which opens the heating circuit is operated by the mercury column being brought in contact with the lower wire, while the relay controlling the cooling system is operated by the mercury coming in contact with the upper wire. *The exhaustion of the air from above the top of the mercury column keeps the contact surfaces clean and bright.*

The thermostat operates on the heating or the cooling circuit according as the temperature of the room is lower or higher than the desired temperature of the thermostat. The 110-volt heating circuit is controlled directly by the relay, arcing being prevented by connecting a 2-microfarad condenser across the contact points. The relay operating the cooling system has a two-point control, one for closing and the other for opening the valve. The valve is so arranged that when it is turned to its position of maximum flow, the circuit of the motor controlling it is

[1] Abstract of a paper presented at the New York meeting of the Physical Society, Dec. 29–30, 1905.

automatically broken, and the motor is connected with the closing point of the relay. When the tank has been sufficiently cooled and the relay armature is released, the motor again operates until the valve is closed, when the circuit is again automatically broken and the motor connected with the opposite point of the relay.

The glass bulb containing the acetone is about 2.5 cm. in diameter and 40 cm. long, while the diameter of the mercurial column is 1.6 millimeters. This regulator has been found to maintain the temperature of a bath containing 400 liters of water constant to within less than one fiftieth of a degree C. There is considerable lag in the temperature of the acetone in a bulb of this form, and the sensibility could undoubtedly be made greater for the same volume of liquid by increasing the length of the bulb. It is necessary in using acetone to protect the grease upon the stop-cock by means of a mercury seal, which is easily done by introducing a short U-tube between the bulb and the stop-cock.

An Attempt to Explain the Cause of the Pressure-Shift and the Broadening of Spectrum Lines.[1]

By W. J. Humphreys.

FROM the experimental work of J. J. Thomson, Zeeman, and others, it is assumed that an atom, at least when luminous, possesses a magnetic field of its own, due to ions rotating in closed orbits. These atoms by rushing to and from each other, will through induction increase and decrease the periods of ionic rotation. There will be Zeeman effects, the atoms themselves furnishing the magnetic fields. This leads naturally to the production of lines of finite width, which width will increase with increased density. It also leads to a shift of the lines as a whole to the *red* end of the spectrum, and in a manner quite in accord with experimental observations.

This explanation of spectroscopic phenomena is offered only as a working hypothesis, suggestive of valuable experimentation.

The Mount Weather Research Observatory.[1]

By W. J. Humphreys.

THE vast economic importance of weather forecasts makes it imperative that their accuracy and range be made as great as possible. The U. S. Weather Bureau has, therefore, begun the construction of a group of observatories and laboratories to be devoted to investigations that

[1] Abstract of a paper presented at the New York meeting of the Physical Society, Dec. 29–30, 1905.

bear on meteorological problems. These consist chiefly of a weather station, now equipped and in use; a balloon and kite plant, about ready for work; two buildings devoted to the study of terrestrial magnetism, the equipment of which is now being installed; a physical laboratory, in course of construction; and a solar physics observatory, for which plans are being considered.

All these buildings are situated on the same reservation, on the crest of the Blue Ridge, in Northern Virginia, away from the dust of cities, and the jars of traffic.

Any thing that bears directly or indirectly on meteorological problems will be regarded as a fit subject for investigation; and each investigator will be given full credit for that which he himself has done.

It is earnestly desired that the relation between this observatory and other institutions shall be one of mutual helpfulness, and much has already happened to encourage us in the belief that this desire will be fulfilled.